NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL REPORT

Logistical Impact Study of Photovoltaic Power Converter Technology to the United States Army and the United States Marine Corps

---

By: James S. Whiteker,
Jason A. Hamilton, and
Steven A. Sablan
December 2004

Advisors: Ron B. Tudor,
Donald R. Eaton,
John K. Shank

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2004	**3. REPORT TYPE AND DATES COVERED** MBA Professional Report	
4. TITLE AND SUBTITLE: Logistical Impact Study of Photovoltaic Power Converter Technology to the United States Army and the United States Marine Corps			**5. FUNDING NUMBERS**
6. AUTHOR(S) James S. Whiteker, Jason A. Hamilton, and Steven A. Sablan			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) XVIII Airborne Corps, United States Army Marine Corps Systems Command Defense Advanced Research Projects Agency			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this report are those of the author(s) and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

The purpose of this MBA Project was to analyze the logistical and fiscal impact of replacing selected disposable batteries with rechargeable batteries and photovoltaic power converter chargers within Army and Marine Corps infantry battalions. This project was conducted with the sponsorship and assistance XVIII Airborne Corps, Marine Corps Systems Command, Fleet Numerical, and the Defense Advanced Research Projects Agency. The goal of this project was to identify how this new technology could be incorporated into current combat gear and what impact such an incorporation of the technology would have in decreasing the infantryman's combat load, reducing expenditures on batteries, and relieving the overall logistical burden for the subject services.

14. SUBJECT TERMS solar power, photovoltaics, rechargeable batteries, logistics, BA-5590, BB-390, BB-2590, PVPCT			**15. NUMBER OF PAGES** 111
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

LOGISTICAL IMPACT STUDY OF PHOTOVOLTAIC POWER CONVERTER TECHNOLOGY TO THE UNITED STATES ARMY AND THE UNITED STATES MARINE CORPS

James S. Whiteker, Major, United States Marine Corps
Jason A. Hamilton, Captain, United States Marine Corps
Steven A. Sablan, Captain, United States Marine Corps

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

NAVAL POSTGRADUATE SCHOOL
December 2004

Authors: ____
James S. Whiteker

____
Jason A. Hamilton

____
Steven A. Sablan

Approved by: ____
Ron B. Tudor, Lead Advisor

____
Donald R. Eaton, Support Advisor

____
John K. Shank, Support Advisor

____
Douglas A. Brook, Dean
Graduate School of Business and Public Policy

THIS PAGE INTENTIONALLY LEFT BLANK

LOGISTICAL IMPACT STUDY OF PHOTOVOLTAIC POWER CONVERTER TECHNOLOGY TO THE UNITED STATES ARMY AND THE UNITED STATES MARINE CORPS

ABSTRACT

Current disposable batteries are a fiscal and logistical burden to both the Army and the Marine Corps. The need for a genuine expeditionary rechargeable system has always existed. Current technology has remained tied to infrastructure of some type and thus the effort to field rechargeable batteries has been impractical for forces that operate away from this support structure for extended periods of time. Photo Voltaic Power sources - solar power, promised great strides in this area, yet up until now it has been an inefficient and fragile means to generate energy. The Photovoltaic Power Converter seeks to overcome these deficiencies and bridge the gap to provide the expeditionary recharging capability the military is seeking. This capability will yield two significant impacts favorable to the Department of Defense (DoD) and using units: significant weight reductions in combat loads, and a lowered fiscal burden.

The purpose of this MBA Project was to analyze the logistical and fiscal impact of replacing selected disposable batteries with rechargeable batteries and photovoltaic power converter chargers within army and Marine Corps infantry battalions. This project was conducted with the sponsorship and assistance XVIII Airborne Corps, Marine Corps Systems Command, Fleet Numerical, and the Defense Advanced Research Projects Agency. The goal of this project was to identify how this new technology could be incorporated into current combat gear and what impact such an incorporation of the technology would have in decreasing the infantryman's combat load, reducing expenditures on batteries, and relieving the overall logistical burden for the subject services.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

We would like to thank our wives and children for their steadfast support and understanding throughout our time here at the Naval Postgraduate School. Though it has been said that behind every great man is a great woman, they have proven that one need not necessarily be a great man to have a great woman supporting him. We thank Professor Ron Tudor for introducing us to this project. Though there were some rocky moments along the way, the experience turned out to be greatly enriching. We thank Admiral Don Eaton for giving us the 10,000 foot view and giving us pointers on how to write a paper that would grab the attention of a flag officer. We thank Professor John Shank for his candid and thorough feedback as well as his dogged determination to see us through this endeavor. We would also like to thank Major Steve Ansley, USA, and Major Lewis Phillips, USA, for their tremendous contribution to Chapter II.

Lastly, though they will probably never know, we would like to thank Morgan’s Coffee and Tea in Monterey, whose early morning caffeine infusions, complimentary wireless internet access, and colorful clientele provided a capable and stimulating environment in which to conduct our Tuesday and Thursday morning off-site meetings.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The DoD is currently transitioning from disposable batteries to rechargeable batteries. The purpose of this MBA Project was to analyze the logistical and fiscal impact of replacing selected disposable batteries with rechargeable batteries and photovoltaic power converter chargers, specifically the PVPCT manufactured by Atira Technologies, to help facilitate this transition. This project focused specifically on offsetting the consumption of BA-5590 batteries, but can be applied with minimal modification to any disposable battery currently in use. The goal of this project was to identify how incorporation of the technology will impact the infantryman's combat load, possible reductions in acquisitions and transportation expenditures on batteries, and relieving the overall logistical burden for the subject services.

As a result of the analysis, significant economies in both weight and cost can be realized by units incorporating PVPCT and rechargeable batteries, specifically the BB-2590. The extent of this economy is dependent on the unit's proximity to logistic infrastructure and the mission profile that they are currently operating within. An appropriate mix of these assets should be acquired by units and this mix must be based upon the unit's requirements, taking into consideration their access to infrastructure, the anticipated operating environment, and the expected duration of operations. By incorporating this technology, the overall logistic burden to individual organizations can be greatly reduced as numbers of batteries consumed rapidly decreases, and as many current fuel and electricity costs are replaced by solar power collection. Atira, the company that manufacturers the PVPCT, has already configured the system to act as the midpoint between any number of solar arrays and then plug directly into a BB-2590. Atira's controller technology is not limited to solar input. With this technology, battery charging capability can additionally be harnessed and channeled into batteries from vehicle alternators, wind power, or various other sources without any additional conventional charger.

In its proposed use, each PVPCT power system would consist of one PVPCT controller, one solar array and a total of four BB-2590 batteries. This system weighs 16.8 lbs and costs approximately $2,180. This system would provide indefinite operational

capability, as each BB-2590 is capable of approximately 1200 charge cycles. In a break-even analysis for weight and cost, the PVPCT system becomes more economical in terms of weight when the mission requires the using unit to be away from re-supply for as few as 24 hours (generally speaking – the actual time is dependent on the type of powered equipment being considered). In terms of cost, the PVPCT system with four BB-2590s reaches breakeven with disposable batteries at the 220 operational hour mark. However, the cost and weight economies dramatically increase as the scope of operations increase. In larger operations (OIF for example) the quantities of disposable batteries consumed becomes tremendously expensive. At the highest point during OIF, approximately 180,000 BA-5590s were consumed per month, which equates to an acquisition cost of $19,500,000 per month, and transportation costs of nearly $1,750,000. The incorporation of PVPCT and rechargeable batteries will greatly reduce this expenditure in future operations, and will increase asset availability to transport other critical assets, such as ammunition and medical supplies.

From the outset of this study it has been clear that the military is facing a shift in not only operating procedures but even more so in its business practices. The move from disposable BA-5590s to rechargeable batteries simply makes sense on all levels. Battery expenditures during Operation Iraqi Freedom, the resulting critical shortages, and the subsequent logistical challenges that accompanied this issue nearly brought coalition offensive operations to a halt. By separating the need to re-supply our battery requirements from the real need – portable power – we begin to shift the focus of what is actually required to fill needs and eliminate capability gaps in the military. With the PVPCT, the ability to recharge batteries becomes a viable option not just for units in garrison, but also for the soldiers who are deployed to the forward edge of the battle area.

The rechargeable batteries impart enormous benefits well beyond the tactical level of logistical support, and in reality, they have the greatest cost benefit ratio when analyzed from the perspective of a theater wide logistics structure. From stateside production to worldwide distribution, the idea of filling a current requirement with a small fraction of current expenditures is remarkable and is indicative of the type of Return on Investment that may be realized by a DoD wide adoption of rechargeable batteries and the PVPC technology.

By utilizing this PVPCT power package individual soldiers gain the ability to be self supporting in terms of their power requirements. In its current configuration, the PVPCT gives our Marines an added capability, increased self sufficiency, and increased flexibility that directly impacts the execution of their missions.

In closing, this analysis shows that Atira's technological innovation is a tool that has a significant ability to impact the daily operations and costs of military operations. The prospective economies realized throughout the logistical chain as well as by the individual are substantial enough to push for incorporation of this technology at the earliest possible date.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

> Strategy is the art of the general. And like any other art, it requires patience to work out its basic concepts. But the odd part of it is that among higher commanders that branch of the art most apt to be treated with a broad stroke, though it calls loudest for the sketching-in of minute details, is the logistics of war.
>
> -S.L.A. Marshall
>
> The Soldier's Load and the Mobility of a Nation[1]

A. PREFACE

The modern ground combat force is critically dependent upon portable sources of electrical power. Within the United States Army and United States Marine Corps, the 24-volt BA-5590 non-rechargeable battery and its rechargeable equivalent, the BB-390, are the primary power sources in some of the most critical battlefield equipment. These batteries power such items as the AN/PRC-119 series of radios – the primary tactical communications equipment for infantry, artillery, and armor units. Additionally, these batteries power the AN/PSC-5 portable satellite telephone, the M98A1 Javelin missile system, and the M22E4 tube-launched, optical wire-guided (TOW) missile system, and the AN/USA-12 crew-served weapon night vision sight[2].

Associated with the host of battery types currently used to power essential battlefield equipment is an enormous fiscal burden and logistical tail. These batteries are burdensome to the entire DoD logistics system to acquire, move, and maintain in such vast quantities. Every cubic foot and every pound used to transport, store, and carry batteries on ships, railcars, airplanes, and trucks equates to an opportunity cost in ammunition, fuel, plasma, and other essential battlefield consumables. More importantly, these batteries are cumbersome to the individual soldier and Marine, who physically bear their weight in combat. For example, a Marine artillery forward observation team, which consists of three Marines, normally carries two AN/PRC-119 series radios and requires

1 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pg. 3. (Original work published in 1949)

2 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study*. (MCSC Contract Number M00264-01-D-002). Quantico, VA: Marine Corps Systems Command, pp. B-6 – B-31.

approximately thirty-five pounds of batteries for a one week operation. Our interest is in the greater flexibility that a rechargeable battery affords the operating units and more specifically the ability to recharge these batteries while in an operational environment.

The Photo Voltaic Power Converter Technology (PVPCT) developed and patented by Atira Technologies is the technological development driving this research. The PVPCT is a device that incorporates new control technology that enables a solar charger to charge a battery even if the power output of the solar collector drops below the battery's charging threshold. The PVPCT stores and accumulates the power coming from the solar charger in a set of lithium-ion batteries and transfers it to the specific rechargeable battery used in combat equipment once the accumulated amount in the PVPCT battery exceeds the combat equipment battery's charging threshold.

Through the use of PVPC technology, we hope to enable our soldiers and Marines to lessen their load of, and dependence on, disposable batteries by enabling the individual user to recharge and reutilize batteries. An additional benefit is that this alleviates some of the demand for re-supply of batteries that our troops currently face. This reduced re-supply is also an advantage to the entire supply chain – we propose that the savings incurred through fewer amounts of batteries being purchased, stored, and transported will be substantial.

B. RESEARCH OBJECTIVE

The purpose of this paper is to examine the potential cost and logistical savings gained by replacing traditional disposable batteries with PVPC technology and rechargeable batteries for particular elements within the DoD. Specifically, we focus on the impact that adoption of the PVPCT will have on logistic demands for infantry battalions of the United States Marine Corps.

C. RESEARCH QUESTIONS

1. Primary Research Question

The overall goal of this analysis is to determine what savings, in terms of logistical burden and costs are gained by incorporating PVPC technology in a Marine Corps infantry battalion. We determine this by evaluating the equipment carried by

Marine infantry battalions operating under three different mission profiles. Specifically, we focus on equipment requiring the non-rechargeable 24 volt BA-5590 battery. From this, we determine the electrical load requirements for such equipment under each mission profile. The result of this analysis is the ability to predict how many BA-5590 batteries, or its rechargeable equivalent – the BB-2590, a battalion requires according to each mission profile. Finally, we compare the cost and logistical requirements for the quantity of BA-5590s versus the quantity of BB-2590s incorporating PVPC technology under each mission profile.

2. Secondary Research Questions

a. *Identify the Power Capability Available to the PVPCT and the Batteries with Which the Technology Can be Used.*

b. *What are the Specific Savings, Manifested in the Reduced Quantities of Batteries Required to Power Selected Equipment in the Observed Units?*

c. *What Weight Reductions will be Gained at the Battalion Level?*

d. *What is the Cost to Incorporate the Technology?*

D. SCOPE AND ORGANIZATION

The scope includes: (1) analysis of current battery uses by the Marine infantry battalion and the potential to use PVPCT to recharge some of these batteries; (2) the savings that may be realized from reduced disposable battery usage, and (3) the logistical impact upon the supply chain by reduced acquisitions and usage of disposable batteries.

The paper is organized into five major sections, including this chapter. The second section provides a summary of the history of Atira Technologies and PVPCT. It also briefly discusses alternative energy sources and common definitions that are used in this report. The third section states facts related to current battery consumption, to include the state of disposable battery technology, the state of rechargeable battery technology, a discussion of the mission profiles to be analyzed, and the logistical requirements for each mission profile discussed. It also conveys how rechargeable batteries and PVPCT work. The fourth section provides the analysis of the data

collected, and presents pros and cons for implementation of PVPCT, including specific savings projections. The fifth section summarizes our findings and provides suggestions for possible follow-on research.

E. METHODOLOGY

The methodology used in this thesis research consists of the following steps.

1. Conduct a comprehensive literature search of books, magazine articles, CD-ROM systems, and Internet based materials.

2. Conduct a detailed logistical analysis of the equipment utilized by Marine Corps infantry battalions

3. Conduct interviews, as required, with users and logistics personnel from I Marine Expeditionary Force to gain insight into battery requirements.

F. BENEFITS OF RESEARCH

This research evaluates potential reductions in battery consumption by the ground forces by initiating the recharging of batteries with the photovoltaic power converter. This thesis assesses the benefits, barriers, and risks involved with this newly developed technology, and makes a recommendation about how it should be incorporated by the concerned services.

II. BACKGROUND[3]

A. INTRODUCTION

Experts predict that our sun will continue to burn for about the next seven billion years[4]. Approximately 10 to 15 thousand times the world's daily energy consumption strikes the surface of the Earth in the form of solar energy every day[5]. With such an abundant and, in human terms, "infinite", source of renewable energy it is no wonder that humankind has been using solar energy for thousands of years.

This section provides the reader a broad familiarization with the history of solar power from ancient through modern times. For the purposes of this report, we break the topic of solar power into two broad categories – passive and active – and introduce the reader to the differences in both categories and give examples of each. We further break active solar power into two main categories -- solar thermal and photovoltaic. We then briefly discuss the benefits of photovoltaic power and current technological shortcomings in the process of converting sunlight directly into electricity.

B. A BRIEF HISTORY OF SOLAR POWER

1. Passive Solar Power

Passive solar power refers to using simple devices and architectural design to create light, a flame, or to heat things such as water or the air in a home where the light, heat, or heated water and air are themselves the desired product. Examples of passive solar power are concave mirrors to focus the sun's rays, southern facing windows in homes, glass to trap in the heat of the sun's rays, or a black metal water container used to heat water.

---

3 This chapter is excerpted from a draft MBA professional report by Major Steven Ansley and Major Lewis Phillips entitled Photovoltaic Power Converter: An Acquisition Evaluation. As stated later in this chapter, both this MBA professional report and the report referenced were conducted under the same CRADA agreement with ATIRA Technologies and share the same background.

4 www.encarta.msn.com/encyclopedia_761562112/Sun.html, 28 September 04

5 www.solarserver.de/lexikon/sonnenenergie-e.html, 28 September 04

a. Ancient Uses of Passive Solar Power

The first written account of the use of passive solar energy is from ancient Greece. In the 5th century BCE the Greeks faced a severe scarcity of fuel wood, but they soon realized they could use the sun to help heat their homes.

> Socrates laid out principles of passive solar design
>
> 1. main rooms should face south 2. north side of buildings should be shielded from the cold winds 3. eaves should be added to provide shade for south windows in summer In houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade.[6]

Archeological evidence dating from the 5th century BCE shows that the Greeks actually planned entire cities using this standard house plan to make the best use of the winter sun. The city of Priene, in western Asia Minor, was designed such that all of the houses were oriented with a southern exposure on an east-west/north-south street grid to allow the winter rays of the sun to come into the homes during the entire solar day[7]. This passive solar architecture in the design of homes and buildings stayed relatively unchanged for hundreds of years, until the Romans made some improvements and formally recognized its importance in the law.

With the Roman's introduction of mica or "glass" to cover the southern facing windows, in the first century CE, the solar heating efficiency of the "Greek solar oriented home" was exponentially increased[8]. The Romans also recognized that the right to the sun was of key importance to all their citizens; in the second century CE they passed "domestic solar rights" laws "to ensure that no building blocked solar access to nearby houses."[9] In 37 CE, the Romans constructed the first greenhouse and used it to grow cucumbers for Tiberius Caesar.[10]

---

6 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04
7 Perlin and Butti, www.californiasolarcenter.org/history_passive.html, 29 September 04
8 Perlin and Butti, www.californiasolarcenter.org/history_passive.html, 29 September 04
9 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04
10 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04

In the middle ages an example of solar architecture is found in the Pueblo Indian city of Acoma, using the same classic Greek east-west running home, designed with southern facing windows.[11]

Not everything about the use of solar energy involved the design of dwellings. In 212 BCE, it is reported that Archimedes magnified sunlight using "burning mirrors" [concave mirrors that concentrated the rays of the sun] onto Roman ship sails to set them on fire and repel the Roman invasion of Syracuse [Sicily].[12] Among the many other weapons he created to protect Syracuse, as well as the mathematical principals and genius for which he is probably better remembered, Archimedes seems to have harnessed the power of the sun in an attempt to defend his homeland. Plutarch recounts a first century BCE example "when the sacred flame of Delphi went out, it could only be re-lit by a "pure and unpolluted ray from the sun."[13] Historians believe this was done using Archimedes' method of focusing the sun's energy with concave mirrors.

b. Modern Uses of Passive Solar Power

The classic Greek solar home architecture principles continued to evolve over time and expand their influence around the entire world. During the Renaissance, in the 16th century, this style of home became popular once again in Europe and moved to America around the 18th century.[14]

What was to spark the solar water heater industry in this country in the late 19th and early 20th centuries was born in 1760 when Swiss naturalist Horace de Saussure invented what was to become know as the "hot box."

> De Saussure built a rectangular box out of half-inch pine, insulated the inside, and had the top covered with glass, and had two smaller boxes placed inside. When exposed to the sun, the bottom box heated to 228 degrees F (109 degrees C) or 16 degrees F (9 degrees C) above the boiling point of water.[15]

11 Perlin and Butti, www.californiasolarcenter.org/history_passive.html, 29 September 04

12 http://www.mcs.drexel.edu/~crorres/Archimedes/Mirrors/Tzetzes.html, 30 September 2004

13 Norman, http://eco.utexas.edu/homepages/faculty/Norman/long.extra/Student.F99/solar/car.html, 28 September 04

14 Perlin and Butti, www.californiasolarcenter.org/history_passive.html, 29 September 04

15 Perlin and Butti, www.californiasolarcenter.org/history_solarthermal.html, 29 September 04

By 1891 Clarence Kemp had patented a solar water heater design that "combined the old practice of exposing metal tanks to the sun [on the roof of a house] with the scientific principle of the hot box…"[16] Keeping the tanks inside the glass box allowed the heat to be retained for a much longer period of time than the bare metal tanks alone. There were 1,600 of Kemp's solar water heaters installed in Southern California homes by 1900. By 1941, half the population of Florida was using an improved version of the solar water heater.[17] By the 1920s natural gas discoveries in Southern California, and the ensuing price reduction of this form of energy, effectively ended the solar water heater industry in California. Similarly, by the 1950s, cheap fossil fuel and electricity across the country made solar products relatively too expensive to continue using.[18] Florida's solar water heaters went the same way as California's had two decades earlier. Countries repeated the pattern of abandoning solar power for cheaper fossil fuels as these natural resources were discovered or made readily available.

In countries with few natural resources or unfriendly neighbors with which to trade, as well as in extremely remote areas, solar power is a more attractive option than fossil fuels. This is evident in the similar explosion in the use of solar water heaters in Japan, Australia, and Israel from the late 1960s through the early 1980s. In 1969, 4 million Japanese homes had solar water heaters; today about 10 million Japanese heat their water with solar energy. In 1983, nearly 60 percent of Israeli homes employed solar water heaters; today that figure is greater than 90 percent.[19]

Today the most successful, yet little known, commercial application of passive solar heating is the solar swimming pool heater. The marriage of the pool and solar heating are a great match. The owner of the pool already owns two of the three necessary "pieces of equipment" to make it all work. The pool and its contents are the storage medium for the collected solar energy, while the pool's circulation/filter pump doubles as the engine that drives water through the solar collector. The only thing the pool owner needs to add is the solar collector itself. In the early 1970s, American

16 Perlin and Butti, www.californiasolarcenter.org/history_solarthermal.html, 29 September 04
17 Perlin and Butti, www.californiasolarcenter.org/history_solarthermal.html, 29 September 04

18 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04
19 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04

Freeman Ford developed low-cost plastic tubing to act as the solar collector.[20] The pool pump continuously pushes cooler pool water through the narrow, black, plastic tubing, which the sun heats, and then pushes back into the pool. The Georgia Tech Aquatic Center, the main site of the swimming competitions for the 1996 Summer Olympic Games, used 278 such solar collectors mounted on the center's roof.[21]

Not all uses of solar energy are passive. Since the mid 19th century, people have devised ways to use solar energy in an active capacity to do work in two general ways.

2. Active Solar Power

For this discussion, we refer to active solar power as using solar energy in one of two ways to do work. The first method is solar thermal power, which uses the sun's heat. The second method, commonly known as photovoltaic power, uses the energy in rays of sunlight. Solar thermal power uses the sun to heat water or some other liquid medium in order to directly or indirectly produce vapor, which in turn drives an engine, such as a water pump, or a turbine to create electricity. In contrast, photovoltaic power refers to a method by which sunlight is converted directly into electricity without any moving parts.

a. Solar Thermal Power

In 1861, French mathematics instructor Auguste Mouchout patented the first engine that ran on steam from solar heated water.[22] By 1872, Mouchout had evolved his design into an invention that continually tracked the sun's azimuth and altitude and focused its rays, using a conical polished metal reflector, onto a blackened copper cauldron enclosed in a glass enclosure. This apparatus would produce enough steam to run a one-half horsepower motor, which was typically connected to a water pump.[23] By 1881, the French government, who at first was quite enthusiastic about the prospects of

20 http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 04
21 http://ces.iisc.ernet.in/hpg/envis/olydoc712.html, 30 September 04
22 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
23 Smith, http://www.solarenergy.com/info_history.html, 30 September 04

Mouchout's invention, "deemed the device a technical success but a practical failure" as the cost of coal drastically dropped and made this alternative source of power less attractive.[24]

In 1878, William Adams used many of Mouchout's ideas as a basis for his own solar thermal invention. Adams used 72, 17x10 inch flat mirrors arranged in a semicircle each focused on a cauldron on a raised tower.[25] The entire mirror system could be moved to track the sun on a semicircular track. Adams' design, which became known as the Power Tower or central receiver design, was able to run a 2.5 horsepower steam engine during daylight hours for two weeks, and is the basis for many modern, large-scale, centralized solar plants.[26]

From 1870 through 1888, Swedish born American, John Ericsson invented and continued to refine a new less complex method of focusing and tracking the sun – the parabolic trough.[27] This configuration resembled the polished interior of a 55-gallon drum cut in half along the long axis. It focused the sun in a linear spread, as opposed to the more concentrated single point produced by the semicircular, conical reflectors. Although this focused a less concentrated beam of energy, the design provided for a simpler method to track the sun along a single axis versus the semicircle used in the Power Tower design. The parabolic trough design has become a standard for many of the largest modern solar plants "because it strikes a good engineering compromise between efficiency and ease of operation.[28]

In 1904, Henry Willsie designed a solar thermal motor that could run both day and night. To store the sun's energy, Willsie built large flat-plate collectors that heated hundreds of gallons of water, which he kept warm throughout the night in a large insulated basin. He then submerged a series of tubes, or vaporizing pipes, inside the basin to serve as boilers. When the acting medium, sulfur dioxide, passed through the pipes, it transformed into a high-pressure vapor, which passed to the engine, operated it, and exhausted into a condensing tube. There, the vapor cooled, returned to a liquid state, and

24 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
25 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
26 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
27 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
28 Smith, http://www.solarenergy.com/info_history.html, 30 September 04

was re-circulated for reuse.[29] Like many solar entrepreneurs before him, Willsie planned to market his continuous solar power plant to the world – but due to the relatively large size to power ratio and the technical nature of dealing with sulfur dioxide, there were no interested buyers.

Undeterred, Frank Shuman worked from 1906 through 1912 and coupled all the knowledge and best practices of the past 50 years, developing what would become the standard for modern solar power plants for more than 50 years. In 1912, Shuman's company and its British investors constructed a solar power plant in Cairo, Egypt. The plant utilized a tracking parabolic trough that focused solar energy on a double-paned glass encased cylinder to produce water vapor. The water vapor in turn powered a specifically designed low-pressure steam engine that generated more than 55 horsepower.[30] Thermal mechanical solar power was on its way – or was it? Following Archduke Franz Ferdinand's assassination two months after the final Cairo plant trials, war soon came to Europe's colonial possessions in Africa.[31] Because of the war, the Shuman's power plant was destroyed and all the engineers returned to their respective countries to perform war related tasks. Unfortunately, Shuman died before the war was over and his ideas were postponed for approximately 50 years.

The combination of mature and stable fossil fuels markets, a skeptical public, and a lack of any significant crisis to precipitate massive capital investment in renewable energy sources relegated the solar power movement to a comatose state for the next half century.[32] The OPEC energy crisis in the 1970s reinvigorated interest in solar power.

By the mid 1980s, modern solar engineers had rediscovered that the parabolic trough, as used by Ericsson and Shuman, offered the most economical solution when conducting a cost/benefit analysis in most locations. From the mid 1980s until 1991, when they were forced to declare bankruptcy, the Los Angeles based Luz Company operated nine parabolic trough, steam-powered electric plants, in the Mojave

---

29 Smith, http://www.solarenergy.com/info_history.html, 30 September 04

30 Smith, http://www.solarenergy.com/info_history.html, 30 September 04. The latter two technical innovations, that of double-paned glass and the specifically designed engine were Shuman's own.

31 Smith, http://www.solarenergy.com/info_history.html, 30 September 04, 28 September 04

32 Smith, http://www.solarenergy.com/info_history.html, 30 September 04

desert, producing 355 megawatts of power or 95% of the world's solar based electricity.[33] These plants were referred to as SEGS plants, or solar electric generating system, and all nine, taken over by a separate investor group, are still in operation today.

> During Luz's existence, the cost of solar electricity was cut from 25 cents per kilowatt-hour to less than 8 cents per kilowatt-hour. SEGS failed economically because: (1) natural gas prices and electricity costs did not rise as expected; (2) operating and maintenance costs for the station did not decline as rapidly as had been expected; and (3) key tax incentives were expiring or uncertain.[34]

At about the same time the Luz plants failed, Solar One, a Con Edison/government team Power Tower type solar thermal plant, was also shut down due to its inability to compete with fossil fuel prices. Additionally, the removal of the ten and 15 percent investment and business tax credits for independent power producers, which were subsequently restored in 1992 – one year too late – helped to put the last nail in the coffin for these alternative power plants. In 1996, Solar Two, using much of the equipment form Solar One, stood up as a government-industry pilot program using the same Power Tower concept and the improved conversion technology of molten salt instead of high-energy oil.[35]

Since 1996, there have not been significant advances in the design or uses of solar thermal power in the United States. However, more and more countries are coming on line, experimenting with and making use of solar thermal power.

b. Photovoltaic Power

The term photovoltaic (PV) is a combination of the Greek word for light, *photos*, and a derivative of the last name of Alessandro Volta, a pioneer in the study of electricity.[36] A PV cell converts light from the sun directly into electricity, as opposed to using the heat from the sun to drive a turbine, as does a solar thermal power system.

33 Smith, http://www.solarenergy.com/info_history.html, 30 September 04
34 Department of Energy, Solar Energy Profile, http://eia.doe.gov/cneaf/solar.renewables/page/solarthermal/solarprofile.pdf, 30 September 04
35 Department of Energy, Solar Energy Profile, http://eia.doe.gov/cneaf/solar.renewables/page/solarthermal/solarprofile.pdf, 30 September 04
36 http://www.californiasolarcenter.org/photovoltaics.html, 30 September 04

The direct conversion of light into electricity is explained by what was originally called the photoelectric effect, but is now also called the photovoltaic effect. In 1839, nineteen year-old, French physicist, Edmund Bequerel first observed that certain metals would produce small electrical currents when exposed to sunlight.[37] The explanation of this phenomenon would have to wait until 1905 when Albert Einstein explained to the world the particle/wave duality of light and quantum physics was born. In general, Einstein found the following: light consists of particles (*photons*). The energy of the photons is proportional to the frequency of the light. As long as the energy of the photon exceeds the amount of energy required to keep an electron in the target medium in place, that electron will be ejected, and the movement of all the ejected electrons towards a positive electrode forms an electric current.[38]

In 1876, William Adams and his student Richard Day discovered that solid selenium exhibited the photovoltaic effect.[39] Although selenium was used to make photovoltaic cells, the conductivity was too low to be of any practical purpose except for using as a light meter for photographic equipment; a purpose for which it is still used today.

A major breakthrough occurred in 1953/4 as Gerald Pearson, Daryl Chapin, and Calvin Fuller of Bell Labs, who, when experimenting with silicon, invented the fist solar cells capable of converting enough solar energy into electricity to run typical electrical appliances.[40] These first silicon PV cells converted the sun's energy into electric energy at an inefficient rate of four to six percent. That is, the cells converted four to six percent of the energy they received from the sun into a useable electrical charge. Unfortunately, it cost $1500 per watt to produce a cell, making it cost prohibitive.[41] This was neither efficient nor cost effective enough for the public to use.

Throughout the 1950 and early 1960s, PV cell efficiency continued to increase while cost per watt continued to decrease. By 1958, Hoffman Electronics, the leading manufacturer of silicon solar cells had achieved nine percent efficient PV cells

37 http://encyclobeamia.solarbotics.net/articles/photovoltaic.html, 30 September 04

38 http://www.walter-fendt.de/ph11e/photoeffect.htm, 29 September 04
39 Perlin and Butti, http://www.californiasolarcenter.org/history_pv.html, 28 September 04
40 Perlin and Butti, http://www.californiasolarcenter.org/history_pv.html, 28 September 04
41 http://inventors.about.com/library/inventors/blsolar2.htm, 29 September 04

that produced power at less than $300 per watt. In 1958 and 1959, the United States launched the first PV-powered satellites into space. These systems provided satellite power for over eight years.[42]

As methods of producing silicon and other types of PV cells improved and their efficiency increased, the cost of each watt of power produced decreased. As the cost of the cells and the power went down, more applications of PV power emerged. There are too many applications to mention, however, a few include: off-shore oil rigs, ocean-based meteorological and navigational buoys, nearly all the lighthouses in the U.S., all of the road-side emergency phones in California, many railroad crossing arms and lights, and even powering entire towns. Today, PV cells with efficiency ranges of five to fifteen percent can be purchased on the Internet while developmental cells with efficiencies ranges in excess of 30 percent are not available to the public.

c. Photovoltaic Power Benefits and Shortcomings

Because the technology evaluated in this project is designed to work with PV cells, the discussion of benefits and shortcomings is limited to this specific area of solar energy conversion.

The benefits of using PV solar power are great. Solar energy is a continuously renewable and practically infinite source of energy, as compared to the finite amounts of fossil fuels available. PV cells convert solar energy into electricity without producing any noise. Another clear advantage of PV-produced electricity over fossil and nuclear power is that there are no environmental pollutants created in the power production process. The PV process has no moving parts to breakdown, requires little maintenance, and is a completely scaleable technology. The existence of solar powered calculators and buildings illustrates the scalability of PV technology. In addition, the further one gets geographically from a traditional power source, the more economical PV electricity becomes.

Although there are many benefits to using PV technology, the primary shortcoming is the efficiency of PV systems to convert light into electricity. As indicated

42 http://inventors.about.com/library/inventors/blsolar2.htm, 29 September 04

previously, current systems are on average about ten percent efficient. Until a technological solution could be introduced that can substantially increase the efficiency of photovoltaic power systems, traditional power sources such as fossil fuel continue to prevail as the preferred source of energy production. In early 2003, a company named ATIRA Technologies announced they had developed a new device, dubbed a Photovoltaic Power Converter that could potentially address the shortfalls prevalent in the PV power industry, and enhance the benefits derived from the use of solar energy.

C. ATIRA TECHNOLIGIES

Stefan Matan and Marty Lettunich co-founded ATIRA Technologies in 2003. Inserted below is Mr. Matan's personal written account of the company's history to include the inspiration for the company name and its primary product.

> While researching potential company names, it was clear that a technology that would have such a large impact on the environment should have a name that could coincide with our belief that our products are good for the future of the earth. It was also decided that an environmentally conscious identity is important in today's business world and that one word names are easy to remember and can say much about a company. When we came across the name Atira, the Pawnee Goddess of Mother Earth, it was obvious we had a winner, for not only the word itself but its meaning as well. Because the earth receives the sun's light, we exist and because of the power of the light, we survive and because man requires power to sustain society, we need resources that provide the power and do not deplete the earth. Power does not get lost-it is transferred from one kind to another.
>
> The idea behind the technology began many years ago when I was a teenager. I was looking at clear glasses, which held water at a summer wedding party. Some of them were half-empty, some of them one third full, but all had some liquid left. I imagined the glasses as being batteries with some charge left and was thinking-what if it were possible to collect all the residue and useless energy and harness it. I was thinking about an electronic device called a switcher with PWM (Pulse Width Modulation). Today these are available everywhere. A couple of years ago, during the California energy crisis the idea came back again when a friend of mine asked me to create a noiseless generator to provide energy for houses. It was a very easy task with today's technologies, but I ran into the problem that solar panels were good only when the sun was shining. There was potential that was untapped during low-light conditions. I remembered the glasses with water from that party again and decided to create a way to

> take that energy and make it useful. I looked for literature on the subject, but nothing was even close to my idea. So I began with the basics, creating a new mathematical model of how to organize the electrons and retrieve the energy under low light conditions. In addition to a successful model, another outcome was the ability for the device to power itself from its own energy source. I had, to put it simply, created a pump for the electrons and the solar cube was born. Obviously, I had something new on my hands. Through a mutual friend, I was introduced to David Tinsley and Marty Lettunich and ATIRA Technologies was founded.43

As discussed previously the primary shortcoming is the efficiency of PV systems to convert light into electricity. The result of Mr. Matan's inspiration is a technological solution that addresses this shortcoming by increasing the usable output of the photovoltaic conversion process.

D. ATIRA TECHNOLOGIES AND THE NAVAL POST-GRADUATE SCHOOL[44]

The Graduate School of Business and Public Policy (BPP) is one of four schools that organizes and conducts research projects at the Naval Postgraduate School (NPS). "BPP is responsible for eight graduate academic programs and awards eight graduate degrees. The largest program is the resident defense-focused Master of Business Administration (MBA) program."[45] In 2003, Professor Ron B. Tudor, a lecturer for the Graduate School of Business and Public Policy, was working on a project involving members of the private sector when Marty Lettunich, CEO and co-founder of ATIRA, approached him. Mr. Lettunich informed Professor Tudor of an exciting new technology developed and patented by ATIRA. Mr. Lettunich, with no military background, provided a general description of the Photovoltaic Power Converter and wondered if the product potentially had defense related applications. He asked Professor Tudor if NPS could assist in the research and development of the product, specifically to identify potential military applications. Although recognizing that the concept of PVPCT had

43 *Mr. Matan's* account was edited for content and clarity

44 The information provided in this section was obtained from an interview conducted by *Major Steve Ansley and Major Lewis Phillips* with Professor Ron Tudor, 13 October 04, GSBPP, NPS, Monterey, CA

45 Naval Postgraduate School Graduate School of Business and Public Policy Programs, http://www.nps.navy.mil/gsbpp/programs.htm, 18 October 04

tremendous potential military applications, Professor Tudor required an organization within the DoD to sponsor the research, and an independent validation of the PVPC technology.

Ultimately, Lieutenant General J.R. Vines, Commander of the U.S. Army 18th Airborne Corps, expressed interest in potential military applications of PVPCT and agreed to sponsor the research. Subsequent correspondence between NPS and Lieutenant General Vines resulted in a NPS research initiation proposal approved by Lieutenant General Vines, which was endorsed by M.A. Gallagher, the Program Manager for Expeditionary Power Systems, Marine Corps Systems Command.

While awaiting the signature approval from LTG Vines; Professor Tudor expedited the initial validation of the technology. He contacted Dr. Sherif Michael, an Associate Professor of the Graduate School of Engineering and Applied Sciences at NPS, and requested he review the PVPCT. Skeptical that the PVPCT could in fact perform as proclaimed and that the technology was valid, Dr. Michael nevertheless agreed to a demonstration. Following the demonstration, Dr. Michael reversed his position and indicated that the technology was likely valid and if further testing proved favorable, its potential applications could revolutionize the solar power industry.

With both of his requirements essentially met, Professor Tudor proposed a formal agreement between NPS and ATIRA in the form of a Cooperative Research and Development Agreement (CRADA). A CRADA is a written agreement between a private company and a government agency to work together on a project. Created as a result of the Stevenson-Wydler Technology Innovation Act of 1980 and amended by the Federal Technology Transfer Act of 1986, a CRADA allows the Federal government and non-Federal partners to optimize their resources, share technical expertise in a protected environment, share intellectual property emerging from the effort, and speed the commercialization of federally developed technology. A CRADA can provide incentives that help speed the commercialization of federally developed technology, protect any proprietary information brought to the CRADA effort by the partner, and allow all parties to the CRADA to keep research results emerging from the CRADA confidential and free from disclosure through the Freedom of Information Act for up to five years. Further, a

CRADA allows the government and the partner to share patents and patent licenses and permits one partner to retain exclusive rights to a patent or patent license.[46]

The proposed CRADA between NPS and ATIRA establishes the roles and responsibilities of each organization, referred to in the CRADA as collaborators. Under the proposed CRADA, NPS requested funding from ATIRA to conduct research and testing of ATIRA's technology and assist ATIRA to transfer the technology into products that the DoD may use in both tactical and operational environments.[47]

With a CRADA in the works and armed with a sponsor and initial validation for the PVPCT, Professor Tudor began soliciting students interested in conducting research as an MBA project. After meeting with multiple students, Professor Tudor approved two primary topics for research. The abstracts for both projects are below for review:

Logistical Impact Study of Photovoltaic Power Converter Technology To The United States Army And The United States Marine Corps

> The purpose of this MBA Project was to analyze the logistical and fiscal impact of replacing selected disposable batteries with rechargeable batteries and photovoltaic power converter chargers within army and Marine Corps infantry battalions. This project was conducted with the sponsorship and assistance of XVIII Airborne Corps, Marine Corps Systems Command, Fleet Numerical, and the Defense Advanced Research Projects Agency. The goal of this project was to identify how this new technology could be incorporated into current combat gear and what impact such an incorporation of the technology would have in decreasing the infantryman's combat load, reducing expenditures on batteries, and relieving the overall logistical burden for the subject services.

Photovoltaic Power Converter: An Acquisition Evaluation

> The purpose of this project is to examine the Photo Voltaic Power Converter Technology, developed and patented by Atira, as a potential Department of Defense Acquisition program/project. Specifically the project will focus on the Technology Readiness Level (TRL), Critical Operational Issues (COI), and Key Performance Parameters (KPP). The project will evaluate and identify the current Technology Readiness Level (TRL) of the PVPC and develop recommended KPPs and COIs for the

46 www.usgs.gov/tech-transfer/what-crada.html, 29 September 04

47 Navy Cooperative Research Agreement, NPS and ATIRA Technologies, Low-Light Solar Charger, pg. 7.

system. Additionally we will recommend the appropriate insertion point of the PVPC into the DoD acquisition process.

E. SUMMARY

The use of the sun to accomplish the goals of humankind is an idea that has been around since the height of the Greek civilization. At first, the sun was used to passively heat homes and water and later to power electricity-generating turbines. The past century has seen the discovery and advancement of photovoltaic power from a scientific novelty to a commercially viable alternative to powering anything from small appliances to large office buildings.

Atira Technologies has developed a breakthrough technology that allows for the generation of electricity through photovoltaic power in low light conditions. Additionally, the system developed by Atira allows the user to store the electricity generated for later use. This technology has gained attention at the highest levels of command within the U.S. Army's XVIII Airborne Corps for its potential applications within the DoD. Of special interest is how this technology may be used to reduce the reliance of combat soldiers and Marines on disposable batteries. In the following chapters, we show the cost and logistical burden savings that can be realized by army and Marine Corps infantry units by substituting disposable batteries with rechargeable batteries coupled with Photovoltaic Power Converter Technology.

THIS PAGE INTENTIONALLY LEFT BLANK

III. FACTS REGARDING BATTERY CONSUMPTION IN THE DOD

A. INTRODUCTION

Throughout the twentieth century, a technological explosion has fueled innovation throughout the world. Towards the end of the century the DoD was at the forefront of this endeavor, rapidly acquiring new equipment that incorporated technological advances. The goal of this rapid pace of development was to ensure that American military forces would have the best equipment available whenever they entered into an armed conflict. To facilitate this goal, equipment was designed to be as powerful and portable as possible. To accommodate both of these requirements, huge demands were placed on the capabilities of batteries to power these complex systems.

Today, batteries continue to play a crucial role on the battlefield. They power portable equipment ranging from Night Vision Goggles (NVGs) to targeting systems on Javelin missile systems to detection devices in Nuclear, Biological and Chemical (NBC) alarms. Additionally, and of critical importance, all portable radios rely on batteries to operate. "Effective communications is the key to success of the battlefield" is a popular axiom espoused by many military officers that reveals the importance placed on reliable communications.

The primary battery that drives portable communications systems is the BA-5590. The BA-5590 is used by the main man-portable radios in the military, as well as multiple other powered systems.

1. BA-5590 Description

The BA-5590 is the most common battery in use in the military. It is approximately 2.3 pounds, and currently costs around $107 (including a $30 disposal fee). A pallet consists of 2000 BA-5590s, takes up 63 cu ft, and weighs 4600 lbs. This battery is rated at 7.2 Ah at 70 ^{0}F and 5.6 Ah at -20 ^{0}F.[48] Used by the United States military in numerous applications over the past 10 - 15 years, the BA-5590 is the only

48 http://www.defense-update.com/products/ba5590.htm, 24 September 04

lithium technology currently available that has a proven successful record in combat situations. With a nominal 200 mA drain in typical use, the battery can provide 28 hours of operation at the minimum operating temperature (36 hours at a normal operating temperature of 70 degrees).[49] Its primary drawback is that the BA-5590 does not have a charge indicator that is cost effective. Thus, this accessory has never been pursued in Government applications. It was deemed that charge indicators were too expensive to be used with a disposable battery.[50] As a result of the missing charge indicators, the unofficial DoD policy has been to discard the BA-5590s after 24 hours of operations, even though the actual lifespan of the battery varies between 28 and 36 hours depending on temperature. As an added safety precaution, in recent combat operations soldiers in many units were instructed to change their BA-5590s every four hours.[51]

B. CURRENT BATTERY TECHNOLOGY

1. BA-5590 Consumption and Related Costs

BA-5590s are currently in use by every service in the DoD. They power such communications assets as the PRC 104/113/117/119/138 radios, as well as the LST 4, HST 4/5, the Motorola URC and LST, and the MXF-707 series. When used in man-pack radios, BA-5590s are typically used in parallel to extend operation time and to facilitate battery change without having to exit the net by powering down the radio.

Due to the extent of their application, the BA-5590 represents a significant portion of DoD battery consumption. Current DoD peacetime consumption of BA-5590s is not readily available, however, as of 1997, the U.S. Army was consuming about 350,000 BA-5590s per year[52], which equates to about $22,750,000. To put this in perspective, total Army expenditures for batteries in 1996 was about $100,000,000.[53] Thanks to standardization practices and a growing use of rechargeable batteries, the Army reduced their total battery consumption to $75,000,000 in 2002.[54] The Marine

49 http://www.defense-update.com/products/ba5590.htm, 24 September 04
50 http://www.defense-update.com/products/ba5590.htm, 24 September 04
51 http://www.batteriesdigest.com/iraqi.htm, 26 September 04
52 http://defenselink.mil/speeches/1997/t19970311-lynn.html, 24 September 04
53 http://dsp.dla.mil/documents/cases/Army-battery-stdzn.pdf, 26 September 04
54 http://dsp.dla.mil/documents/cases/Army-battery-stdzn.pdf, 26 September 04

Corps is also a large consumer of disposable batteries. In 2000, I MEF was consuming approximately $3,000,000 per year for BA-5590s.[55] Assuming they represent about 25% of the Marine Corps battery consumption, the USMC figure is approximately $12,000,000 (about 169,000 batteries per year).

During Operation Iraqi Freedom, the tremendous demand for BA-5590s surpassed available supply. In fact, insufficient supply hampered operations and threatened to force the U.S. military to cease operations.[56] "We literally [came] within days of running out of these batteries – where major combat operations would either have ceased or changed in their character because of the lack of battery support," said Navy Captain Clark Driscoll, the Defense Contract Management Agency liaison to the Joint Staff, in remarks to the Tri-Service Power Expo in Norfolk, Virginia.[57]

There were three factors that kept the military from running out of batteries – conservation methods, a quick war, and dedication from battery manufacturers who were able to rapidly ramp up production to fill critical requirements. The conservation methods included consolidating BA-5590s worldwide for immediate routing to Kuwait, as well as transferring BA-5590s from non combat units throughout the world to those units directly involved with combat operations.

As a result of these efforts, airplane loads of batteries were flown on Air Force cargo planes from Charleston, South Carolina to Kuwait – planes that could have otherwise carried fuel, ammunition or medical supplies had batteries not become so scarce. At its height, one airplane load of BA-5590s a day was flying out of Charleston, a practice that was expected to continue for many weeks.[58]

Determining the actual demand for batteries throughout the theater was extremely difficult to establish – for one, nobody knew exactly how many radios, Javelin missile

---

55 http://www.darpa.mil/dso/thrust/matdev/palmpower/presentations/hartman.pdf, 25 September 04

56 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

57 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

58 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

systems, and NBC alarms were in theater.[59] This set the foundation for the shortage, as initial battery supplies were sent via ship, a roughly three-week transit time. The initial assumption was that the flow of batteries would be sufficient to meet demand. However, two weeks into the war, it was clear that batteries were being consumed at an alarming rate. Four months into the war, specific demand was still uncertain, but some general consumption numbers were being established – the Marine Corps, for example, was consuming a mean of 3,028 BA-5590 batteries *per day*.[60] It is estimated that this represents about half of the consumption on the battlefield, resulting in a total consumption of approximately 6,056 batteries per day (or 181,680 batteries per month) at the height of the ground campaign.[61] This equates to an acquisition cost of about $14,000,000 per month, plus related transportation costs and a monthly estimated disposal cost of nearly $5,500,000. For transportation purposes, this equates to approximately 91 pallets of batteries per month and a total weight and volume requirement of 418,600 lbs and 5733 cu. ft per month.

2. Costs Related to Logistic Support for Current Demand

Acquisition costs are not the only consideration when evaluating the use of the BA-5590. Research identified an approximate usage rate of 91 pallets of batteries per month and a total weight and volume requirement of 418,600 lbs and 5733 cu. ft per month. The majority of BA-5590s were shipped by military cargo planes, which therefore displaced other critical cargo. In addition to displacing other critical cargo, the actual costs involved shipping batteries via AMC were tremendous. With 91 pallets a month being consumed, the rate is about three pallets per day. Each pallet (2000 batteries, 4600 lbs, 64cu ft) costs approximately $19,320 (or about $9.66 per battery) for AMC to deliver from Atlanta Georgia to Kuwait City.[62] Therefore, daily transportation costs for the BA-5590 via AMC were about $57,960 or $1,738,800 per month. For proper disposal of spent batteries, transportation back to the states is the same, an

59 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

60 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

61 Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, September 2003, Volume 88, Issue 598, pg. 16.

62 http://www.public.amc.af.mil/business/fm/fy04dod.pdf, 28 September 04

additional $1,738,800 per month. Total monthly cost associated with BA-5590 during Operation Iraqi Freedom = (14,000,000 + 5,500,000 + 3,477,600) = about $22,977,600 per month.

3. Current Alternatives to BA-5590 Use

Currently, the most applicable alternative to the use of BA-5590s comes in the form of rechargeable batteries. The direct replacement for the BA-5590 is the BB-390 and the new BB-2590. The rechargeable batteries require a power source for initial and subsequent charges. The two chargers currently in use are the PP-8444 and the PP-8498. The PP-8498 will charge both the BB-390 and the BB-2590; however, the PP-8444 can only charge BB-390s. Both chargers require AC or DC power to generate a charge.

a. BB-390B Rechargeable Battery

The BB-390B is a rechargeable, Nickel Metal Hydride battery with "State of Charge Display". It has a nominal capacity of 4.9 Ah at 24.0 volts. It has an operating temperature range of -20ºC to +55ºC (-4ºF to +131ºF). The BB-390B has a nominal weight of 3.880 Lb (1.76 Kg), and is sold in a master carton of 10 batteries each, which weighs 40 lbs and requires about .5 cu ft. Each BB-390B costs about $284, which includes a $30 disposal fee.[63] The BB-390B can be recharged about 230 times. At a drain rate of 200mAH, it will provide approximately 24 hours of operation at its optimal temperature (about 66% of the BA-5590 operational time at a similar temperature).

b. BB-2590 Rechargeable Battery

The BB-2590 is a newer rechargeable battery designed to directly replace the BA-5590 and the BB-390B. This battery is composed of two separate Lithium Ion rechargeable cells, each with an individual capacity gauge. It has a capacity of 6.0 Ah at 30.0 volts. It has an operating temperature range of -20 to 60 C (-4ºF to +136ºF). Each battery weighs 3.2 lbs and requires .03 cu ft.[64] At optimal temperatures, the BB-2590 is expected to provide nearly 30 hours of operational time at a 200mAH discharge rate (about 80% of the BA-5590 operational time). Each BB-2590 costs around $330, plus

---

63 http://www.bren-tronics.com/pdf/BB390B.pdf, 17 September 04
64 http://www.bren-tronics.com/pdf/BB2590.pdf, 17 September 04

associated disposal costs. BB-2590s are not considered hazardous material; therefore there are no HAZMAT-associated disposal costs.[65] BB-2590s offer up to 1200 recharging cycles.[66]

c. PP-8444 Battery Charger

The PP-8444 charging unit is capable of recharging two batteries of the same type simultaneously, and fully charging these batteries within two hours. The user must select the specific battery adapter that is required for the individual battery type.

Figure 1. PP-8444 Battery Charger

It can charge numerous types of batteries to include the BB-390; however, it will not recharge the BB-2590. The dimensions of this set are 13.25 inches wide by 10.5 inches deep and 7 inches tall. The unit weighs 12lbs. and requires house or vehicle power to provide a charge for batteries. It has a battery charge indicator and can identify batteries that are internally damaged. Each charger costs approximately $683.[67]

d. PP-8498 Battery Charger

The PP-8498 charging unit is capable of recharging 2 batteries simultaneously and holding up to 6 batteries of the same or different types in queue for

65 http://www.ultralifebatteries.com/techsheets/UBI-5107_UBI-2590.pdf, 26 September 04

66 https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary85256A2B0062C0F7.nsf/, 28 September 04

67 https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary85256A2B0062C0F7.nsf/, 28 September 04

the next automatic charge cycle. It can typically charge up to 8 batteries hands free within 8 hours.

Figure 2. PP-8494 Battery Charger

It charges numerous types of batteries to include BB-390's and BB-2590's. The dimensions of the set are 22.8 inches wide by 14.6 inches deep and 9.0 inches tall. The unit weighs 27.5 lbs and requires house or vehicle power to provide the charge to batteries. In vehicular use, the unit warns users when vehicle battery voltage drops to 22V DC and it shuts down at 21V DC, to prevent completely draining the vehicle's battery. The PP-8498 also contains a battery charge indicator to verify the charge state of any connected battery, and the unit can also identify internally damaged batteries, damaged adapters, and dirty or damaged thermal contacts on BB-390s. Each charger costs approximately $1893.[68]

C. CURRENT MARINE CORPS EQUIPMENT REQUIRING THE BA-5590 OR EQUIVALENT

Driving the requirement for the ever increasing need for batteries is the ever growing equipment lists that are required by ground forces in the conduct of their missions. Both the Army and Marine Corps have thoroughly entrenched the BA-5590 family of batteries as the go-to power source for radios and the man packed anti-tank weapons systems. What follows is a list of the most prominent and widespread equipment using these batteries.

68 https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary85256A2B0062C0F7.nsf/, 28 September 04

1. AN/PRC-119A, D, and F

The AN/PRC-119A, D, and F are the man-pack configurations of the single channel ground and airborne radio system (SINCGARS). The SINCGARS radios systems are composed of interchangeable, modular components sets. The primary component of all SINCGARS radios is the RT-1523 receiver/transmitter (RT).

Figure 3. AN/PRC-119F

The SINCGARS operates in either the single-channel mode on 50 kHz channels or the high frequency mode. Features of this radio include controllable output power, eight non-volatile preset single channels, and six non-volatile frequency hopping preset channels. It operates over the 30 to 87.975 MHz frequency range in 25 KHz increments. The various radio configurations consist of a combination of basic components. These components include: the RT, vehicular mount, power amplifier, and broadband antennas. The number of RTs, amplifiers, installation kits, and man-pack components determine the actual radio configuration and variant. Each radio requires one BA-5590 battery or equivalent providing approximately 32 hours of operating life.[69]

2. AN/PSC-5

The AN/PSC-5 is a portable, battery-operated, half-duplex ultra high frequency (UHF) radio receiver/transmitter. It is primarily employed for long-range over-the-horizon communications. It weighs approximately 14 pounds including antenna and batteries. The AN/PSC-5 provides two-way voice and data communications by satellite.

69 http://www.marcorsyscom.mil/sites/pmcom/sincgars.asp, 05 October 04

It operates on the UHF frequency band over the 225- to 400-MHz range. The AN/PSC-5 requires two BA-5590s or equivalent with an expected battery life of 12 hours.[70]

Figure 4. AN/PSC-5 Tactical Satellite Radio

3. AN/PRC-117F(C)-HQ Joint Tactical Radio System (JTRS)

The AN/PRC-117F(C)-HQ covers the entire 30 to 512 MHz frequency range while offering embedded secured communications (COMSEC) capabilities. It is utilized to communicate between ground forces and supporting air assets and is the replacement for the AN/PRC-113. The radio weighs 9.8 pounds without its batteries. It accepts two BA-5590, BB-390A/U, or BB-590 batteries providing an expected operating life of 36 hours.[71]

Figure 5. AN/PRC-117F

4. AN/PRC-150

The AN/PRC-150 provides half duplex HF and Very High Frequency (VHF) tactical voice and data radio communications and is the replacement for the AN/PRC-138. The 20-watt power output is provided by either two batteries or external electrical

70 http://www.tpub.com/content/USMC/mcr3403b/css/mcr3403b_32.htm, 05 October 04
71 http://www.romad.com/equipment.htm#PRC-117F, 05 October 04

power. Transmission security is provided either through the KY-99 or its embedded TYPE 1 encryption.[72]

Figure 6. AN/PRC-150

5. M98A1 Javelin Missile System Command Launch Unit (CLU)

The Javelin is a man-portable, fire-and-forget missile system employed by dismounted infantry to defeat current and future threat armored combat vehicles. Javelin is intended to replace the M-47 Dragon system in the army and the Marine Corps.

Figure 7. M98A1 Javelin Missile System

The Javelin has significant improvements over Dragon – the Javelin's range of approximately 2,500 meters is more than twice that of its predecessor, the Javelin has secondary capabilities against helicopters and ground-fighting positions, it is equipped with an imaging infrared (I2R) system and a fire-and-forget guided missile. The Javelin's normal engagement mode is top-attack to penetrate a tank's most vulnerable armor. It also has a direct-attack capability to engage targets with overhead cover or in bunkers. Its "soft launch" allows employment from within buildings and enclosed fighting positions. The soft launch signature limits the gunner's exposure to the enemy, thus increasing survivability. Javelin is also much more lethal than Dragon; its dual warhead capability can defeat all known enemy armor systems.

---

72 http://www.rfcomm.harris.com/products/tactical-radio-communications/am-prc-150-hq.pdf, 07 October 04

The Javelin consists of a missile in a disposable launch tube and a reusable Command Launch Unit (CLU) with a trigger mechanism and the integrated day/night sighting device for surveillance, target acquisition, missile launch, and damage assessment as well as built-in test capabilities and associated electronics. Two disposable BA-5590 batteries power the CLU, providing an average of four hours of usage. The Javelin night vision sight (NVS) is a passive I2R system. The NVS enables target detection, identification, and acquisition under degraded visual conditions. It receives and measures IR light emitted by the environment and converts it into an electronic image for the gunner. The complete system, including batteries and one missile, weighs approximately fifteen pounds.[73]

6. M220E4 TOW 2 Missile System and AN/UAS-12C Night Vision Set

The TOW (Tube-Launched, Optically-Tracked, Wire-Guided) Weapon System, with the multi-mission TOW 2A and TOW 2B missiles, is the primary heavy anti-armor weapon system for the army and Marine Corps.

Figure 8. M220E4 TOW 2 Missile System Mounted on a HMMWV

The TOW is in service with over 40 international armed forces and integrated on over 15,000 ground, vehicle, and helicopter platforms worldwide. The TOW 2A missile was developed by Raytheon Missile Systems for the U.S. Army to defeat advances in the armor threat created by the advent of first and second generation Explosive Reactive

73 http://www.fas.org/man/dod-101/sys/land/javelin.htm, 07 October 04

Armor (ERA). The TOW 2 Hardware improvements included a thermal beacon guidance system enabling the gunner to more easily track a target at night and numerous improvements to the missile guidance system.[74] The TOW employs an advanced night sight in the AN/UAS 12 C. It requires four BA5590s, providing ten hours of operation.[75]

7. M22 Chemical Agent Detector and Alarm

The M22 is an "off-the-shelf" automatic chemical agent alarm system capable of detecting and identifying standard blister and nerve agents. The XM22 system is man-portable, operates with no human interface after system start-up, and provides an audio and visual alarm. Another critical feature of the XM22 system is a communications interface to support battlefield automation systems. The unit weighs fifteen pounds with two batteries that supply power for 32 hours.[76]

Figure 9. M22 Chemical Agent Alarm

8. AN/PEQ-1 SOF Laser Marker (SOFLAM)

The AN/PEQ-1 Special Operations Forces (SOF) Laser Marker (SOFLAM) is the SOF-specific laser range finding and target designating unit that provides the capability to locate and designate critical enemy targets for destruction using laser guided ordnance.

74 http://www.hqmc.usmc.mil/factfile.nsf/0/4ba8fle3958ca16d8525628100789abb?OpenDocument, 07 October 04

75 http://www.designation-systems.net/dusrm/m-71.html, 07 October 04

76 http://www.fas.org/man/dod-101/sys/land/m22-acada.htm, 07 October 04

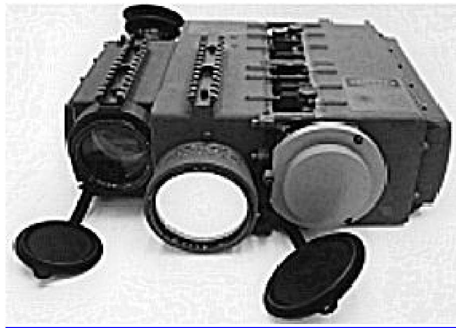

Figure 10. AN/PEQ-1 SOFLAM

The unit is lighter and smaller than more widely-issued laser markers with better reliability and availability than its conventional counterpart. The SOFLAM is currently in use with army Special Forces and Rangers, Navy SEALs, and Air Force Special Tactics Squadrons. It requires five BA 5590s for 5.8 hours of use.[77]

9. Ground Laser Target Designator (GLTD) II

The GLTD II provides ground forces with a compact, lightweight, man-portable laser target designator/rangefinder that is ideally suited for precise delivery of laser guided munitions such as Paveway bombs and Hellfire missiles. Through an RS-422 data link, the GLTD II can be integrated into a digitized, day/night fire control and surveillance system.

Figure 11. Ground Laser Target Designator II

Forward Air Controllers (FACs) rely heavily on GPS devices to locate enemy positions and call in fire against targets. For Operation Iraqi Freedom, the 1st Marine Division employed 19 Ground Laser Target Designator (GLTD) II systems. This system

77 http://www.globalsecurity.org/military/systems/ground/an-peq1.htm, 07 October 04

allows FACs and artillery forward observers to measure the accurate range to a target and to designate it for the delivery of laser-guided munitions.[78]

D. ESTABLISHMENT OF COMMON DEFINITIONS

Before proceeding, it is essential to establish common definitions for some of the terms that are used extensively throughout the remainder of this discussion. In discussing mission profiles, the Army and Marine Corps infantry battalions are the units of interest. The infantry battalion will be defined below. Additionally, combat loads will be addressed – especially in discussing the weight impact of PVPCT. A common understanding of the combat load will be discussed below.

1. The Infantry Battalion

As mentioned above, the infantry battalion is used as the unit of interest in analyzing the impact of PVPCT. Although this discussion applies to both Army and Marine Corps infantry battalions, the template of the Marine Corps infantry battalion is used for discussion. The organization of an infantry battalion differs slightly between the Army and the Marine Corps, but not enough to distinguish between the two when discussing the impact of PVPCT.

Units of interest consist of a headquarters element and five company-sized major elements. Subordinate to the battalion headquarters are three rifle companies, a headquarters and services company, and a weapons company. The basic diagram for this unit of interest, including major subordinate elements, is shown in Figure 12.

78 http://www.dsd.es.northropgrumman.com/laser/GLTD.html, 07 October 04

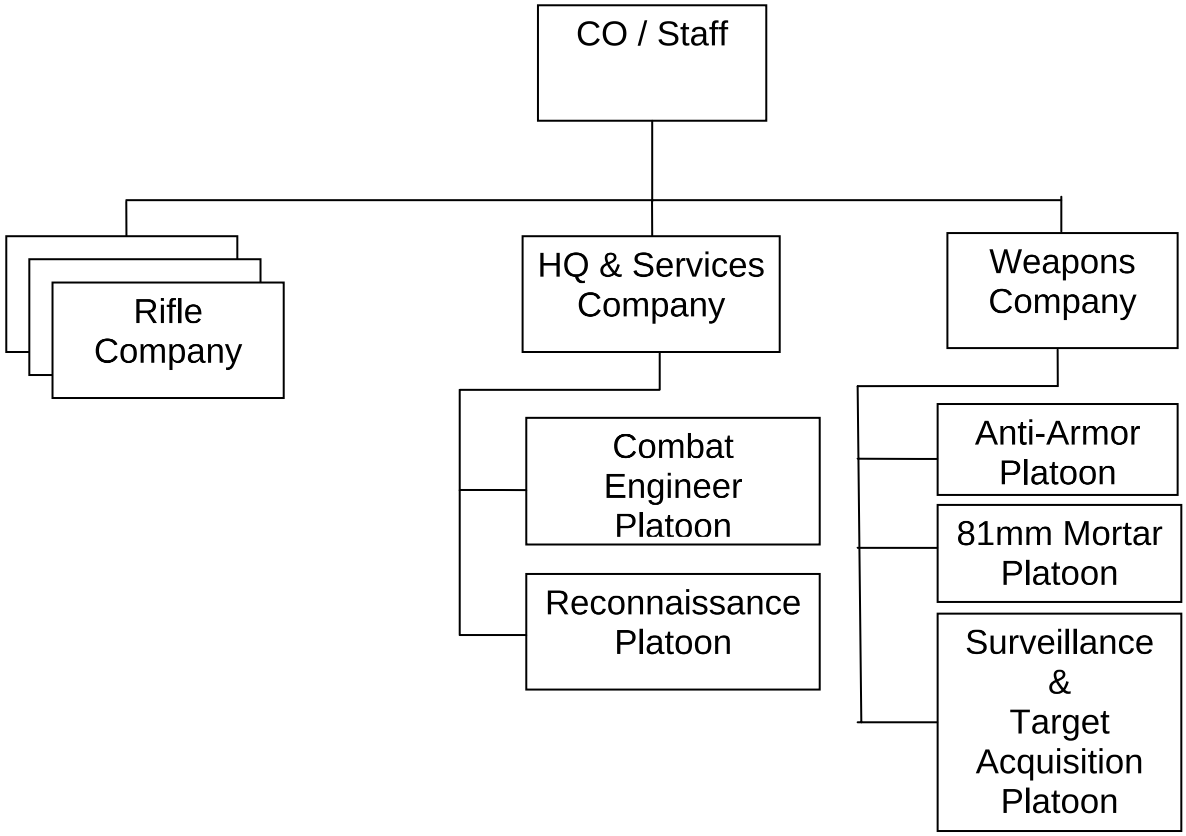

Figure 12. Infantry Battalion Organizational Diagram

Subordinate to the infantry battalion the rifle company is a particular sub-unit of interest. The rifle company consists of a company headquarters, three rifle platoons, and a weapons platoon. Within the weapons platoon are a mortar section, a machine gun section, and an assault section. The basic diagram for a rifle company is shown in Figure 13.

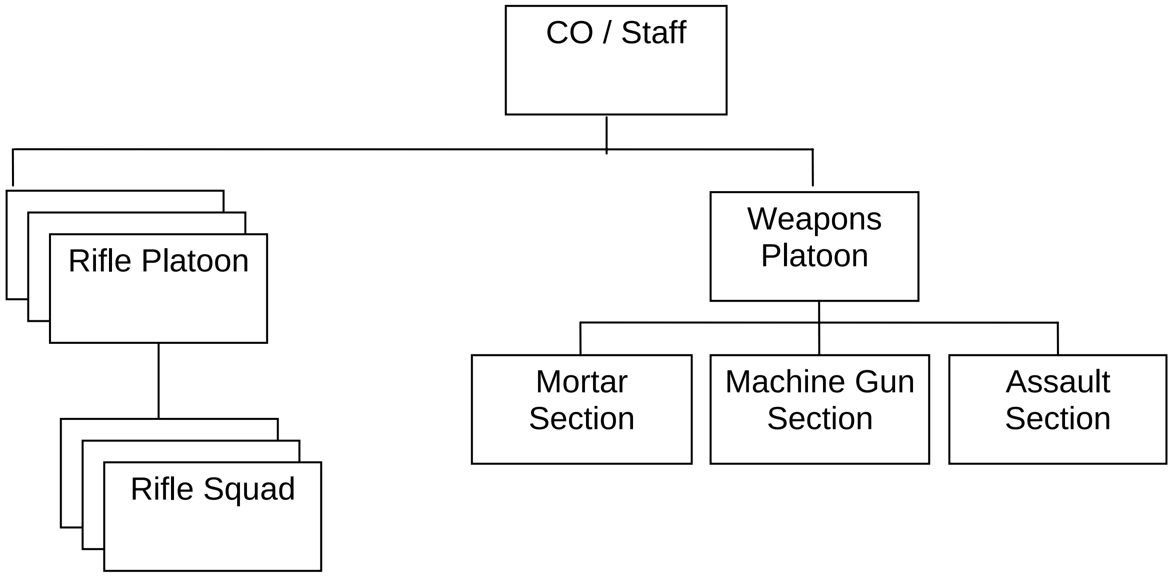

Figure 13. Rifle Company Organizational Diagram

2. Combat Loads

As defined by FM 21-18, *Foot Marches*, the combat load is the minimum mission-essential equipment responsible for carrying out the mission, required for infantrymen to fight and survive immediate combat situations. The combat load is the essential load carried by infantrymen in forward subunits or the load that accompanies infantrymen other than fighting loads. Combat loads are broken into three main categories: emergency approach march load, approach march load, and fighting load.[79]

a. Emergency Approach March Load

Circumstances can require infantrymen to carry loads heavier than 72 pounds, such as approach marches through terrain impassible to vehicles or where ground/air transportation assets are not available; therefore, larger field packs must be carried. These emergency approach march loads can be carried easily by well-conditioned infantrymen. When the mission demands that infantrymen be employed as porters, loads of up to 120 pounds can be carried for several days over distances of 20

79 Headquarters, Department of the Army (1990). *FM 21-18: Foot Marches*, Washington, DC: U.S. Government Printing Office, pg.5-6.

kilometers a day. Although loads of up to 150 pounds are feasible, the infantryman could become overly fatigued or even injured.[80]

b. Approach March Load

The approach march load includes clothing, body armor, weapon, basic load of ammunition, load bearing equipment, small assault pack, or lightly loaded rucksack or poncho roll. On prolonged dynamic operations, the infantryman must carry enough equipment and munitions for fighting and exist until his unit is re-supplied. In offensive operations, infantrymen designated as assault troops need equipment to survive through the consolidation phase, in addition to carrying munitions for the assault. A limit of 72 pounds should be enforced.[81]

c. Fighting Load

The fighting load includes bayonet, weapon, clothing, helmet, load bearing equipment, body armor, and a reduced amount of ammunition. Loads carried by assaulting troops should be kept to a minimum. A limit of 48 pounds should be enforced.[82]

E. DESCRIPTIONS OF SELECTED MISSION PROFILES

In order to evaluate the cost and logistical benefits of employing PVPC technology in combination with rechargeable batteries, three mission profiles were selected for analysis. The mission profiles described below are used to illustrate the integration of PVPC technology over a spectrum of infantry battalion-sized operations. The following chapter compares the costs and logistical considerations for an infantry battalion using disposable batteries versus using PVPC technology for each mission profile.

---

80 Headquarters, Department of the Army (1990). *FM 21-18: Foot Marches*, Washington, DC: U.S. Government Printing Office, pg.5-6.

81 Headquarters, Department of the Army (1990). *FM 21-18: Foot Marches*, Washington, DC: U.S. Government Printing Office, pg.5-6.

82 Headquarters, Department of the Army (1990). *FM 21-18: Foot Marches*, Washington, DC: U.S. Government Printing Office, pg.5-6.

1. Combined Arms Exercise

The Marine Corps' Combined Arms Exercise (CAX) program centers on a series of intense live-fire evolutions and takes place over a three-week period at the Marine Air-Ground Task Force (MAGTF) Training Center located at 29 Palms, California. Ground forces typically involved in the exercise include an infantry battalion reinforced by an artillery battalion, a tank company, an assault amphibious vehicle company, and a combat engineer detachment. The CAX program incorporates a building block approach to learning, rotating units through squad, platoon, company, and battalion-level evolutions, climaxing in a final exercise employing the ground, air, and combat support elements of the MAGTF. The evolutions range in duration from several hours to five days. Between evolutions, units rotate back to an expeditionary camp to plan for follow-on evolutions, re-arm, re-equip, and equipment repair and maintenance. The expeditionary camp includes improved combat support capabilities, with facilities to conduct higher-echelon maintenance.

2. Stability and Support Operations

Stability and support operations are those of the type currently being conducted by coalition forces in Iraq and Afghanistan. Under such operations, the preponderance of support is pulled from the support bases by the ground combat forces. Mission durations for stability and support operations may range from three hours to thirty days. The intensity of missions under this classification range from foot patrols to medium intensity counter-insurgency operations. Tactical vehicles, armor, artillery, as well as assault air assets may be utilized in support of stability and support operations.

3. High Intensity Sustained Combat Operations

High intensity sustained combat operations are those like the initial ground invasion phase conducted during Operation Iraqi Freedom (OIF). Under such operations, it is assumed that ground combat forces derive a majority of their support from their organic logistical trains. As such, the majority of support is pushed from the logistical trains to the ground combat units, which are expected to be constantly in contact with enemy forces. Assets available to conduct re-supply missions between the ground forces

and supporting bases are severely limited and such missions should be expected to take several days to complete. The full spectrum of air and ground-based supporting arms will be fully employed.

F. RECHARGEABLE BATTERIES AND PVPCT

While conventional chargers can recharge batteries in locations with robust infrastructures, they have limited use in forward locations where appropriate vehicles are not as abundant and line-power infrastructure is nonexistent. Rechargeable battery use can thus be separated into two areas – in areas with robust infrastructures, which facilitate charging via AC power (found in structures) or DC power (found in plugging chargers into vehicles), and in areas without the infrastructure to recharge batteries in this manner. It is in the latter area that the PVPCT offers significant capabilities and economies. When coupled with a solar collector, the PVPCT provides the capability to efficiently recharge batteries with great flexibility.

The PVPCT compliments the DoD's intended migration to rechargeable batteries. The PVPCT's ability to more efficiently harness and make use of solar energy provides a flexible capability to units that are geographically removed from a robust infrastructure. In locations with a robust infrastructure, it is easy to have semi- fixed charging stations consisting of vehicles or structures that can serve as battery charging stations and support a relatively unlimited quantity of rechargeable batteries.

However, units that need to remain flexible in terms of geographical displacement and that must endure flexible time constraints cannot depend upon the availability of charging stations. Instead, these units require a charging capability that is flexible and portable. The PVPCT is designed to provide these units with that flexibility. Combined with any number of portable solar collectors, the PVPCT can harness, store and transfer a much greater quantity of solar energy than collectors alone are capable of providing.

Solar collectors alone are only capable of transferring a charge during peak daylight hours, generally only between 10:00 am and 4:00 pm local time, under ideal sunlight conditions. However, the PVPC technology begins to generate a charge as soon as there is any ambient light. This extends the charging window by as much as eight

additional hours a day (potentially doubling possible daily charge capability). Because of this, the PVPCT can charge batteries in much less time than any other solar technology available, and can charge more batteries in any 24 hour window.

1. Solar Panels

There are many types of solar cells that are effective for use with the PVPCT. For the purposes of this discourse, several COTS (Commercial-Off-the-Shelf) variants are presented. Each example was selected based on various characteristics, including flexibility and appropriateness to military operational requirements.

a. UniSolar FLX-32, Flexible 32 Watt Solar Panel

The SmartCharge FLX-32 is a solar collector that can provide 12 amp-hours of charge capacity per day under ideal conditions. Multiple panels may be hooked together to increase collection capability. The FLX-32 offers durable and flexible construction; light weight; maintenance-free; and is weather and sea water resistant.

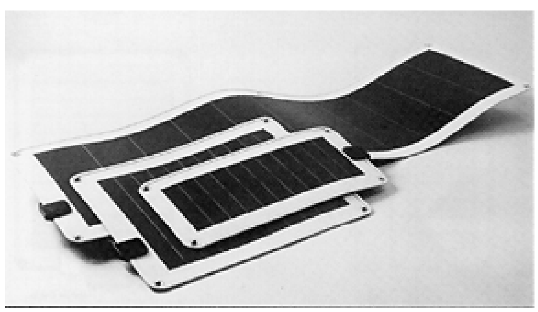

Figure 14. UniSolar FLX-32

It was designed specifically for battery charging or battery maintenance in marine applications as well as for camping, hiking, and other outdoor activities. It is rated at 32 watts of power, is 17 inches wide and 56 inches long and weighs 4.7 pounds.

The FLX-32 comes with a 5 year warranty and costs $242.[83] Operating voltage is 15.4V, operating current is 1.2 Amps, weight is 1.9 lbs, and its dimensions are 12 x 73 inches (12 x 4.25 x 4.5 when rolled).[84]

b. *Iowa Thin Film Technologies Power Film R-15-1200 20W, 12V Thin Film Solar Panel*

Iowa Thin Film Technologies produces a flexible solar panel made with "PowerFilm®, the world's most rollable, lightweight, and durable solar technology. This product is made with professional marine-grade components and rugged UV-stabilized materials. It is waterproof." Cost is $357.77[85]

Figure 15. Iowa Thin Films Technologies R-15-1200

"PowerFilm® is made of silicon, a natural resource in abundant supply. Also PowerFilm® performs well in diverse environments, including hot sun…" These characteristics lend themselves well to DoD usage. This panel is UV resistant, weatherproof, and is designed to operate in diverse conditions including excessive heat as well as cloudy environments. Iowa Thin Film Technologies backs this product with a 3 year warranty.[86]

2. Current PVPCT System Prototype

Atira Technologies has developed several prototype PVPCT systems. The most current prototype is pictured below;

83 http://www.uni-solar.com/cons_products.html, 5 October 04

84 http://www.uni-solar.com/cons_products.html, 5 October 04

85 https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary.nsf, 28 September 04

86 http://www.iowathinfilm.com/products/rollableseries/index.html, 5 October 04

Figure 16. PVPCT System Prototype With Controller and Flexible Solar Array Stowed

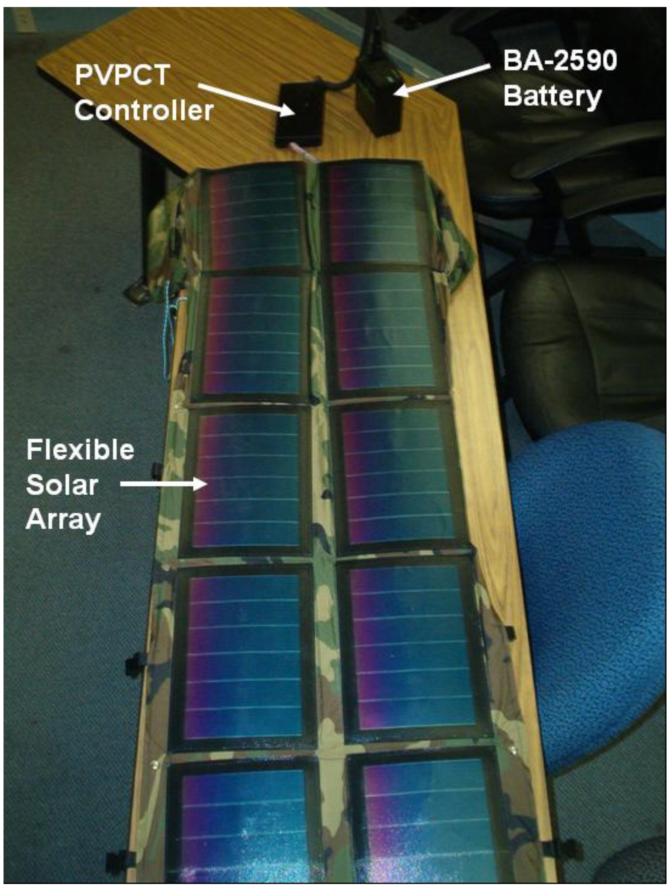

Figure 17. PVPCT System Prototype With Flexible Solar Array Deployed

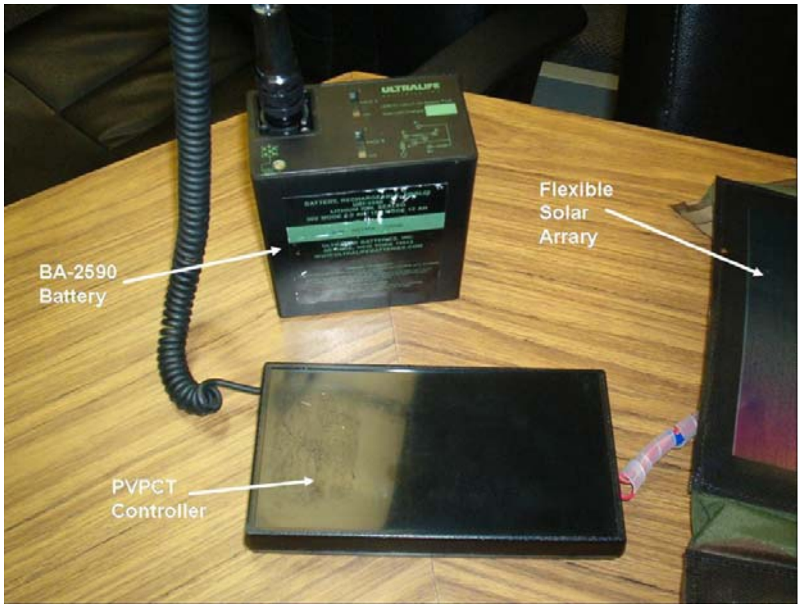

Figure 18. Close-Up of Rechargeable Battery and PVPCT Controller

The current prototype PVPCT system consists of a custom built solar array by Atira, a PVPCT controller, and a BB-2590 rechargeable battery. The current system can fully charge the BB-2590 in less than one solar day.

G SUMMARY

Historically, DoD has been dependent upon disposable battery technology to support equipment utilized by ground combat forces. Due to massive consumption and associated costs the DoD is currently transitioning from the heavy reliance on disposable batteries to the increased flexibility and reduced life cycle costs of rechargeable batteries.

Current charger technology relies on vehicle or AC power to recharge batteries. Chapter IV analyzes the PVPCT to facilitate a paradigm shift towards the incorporation of solar technology in recharging batteries. Several commercially available solar panels have been identified that may interface with PVPCT to provide a more expeditionary form of power charging capability for ground combat forces. The following chapter discusses and analyzes how PVPCT can be incorporated under the three identified mission profiles.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. ANALYSIS

A. DOD PERSPECTIVE ON DISPOSABLE BATTERIES

It has long been recognized that the use of the disposable BA-5590 is not cost effective and that rechargeable batteries and alternative sources of power need to be pursued. In 1997, Larry Lynn, then the director of the Defense Advanced Research Projects Agency (DARPA), testified to the Acquisition and Technology Subcommittee of the Senate Armed Services Committee, regarding the High Energy-Density Power Program, which in part is intended to reduce reliance on BA-5590s:

> The warfighter of the future will be increasingly dependent on electrical systems, and DARPA is developing technologies that enable electronic systems to be more energy efficient. But at the same time, the warfighter must have improved high energy-density power sources to supply needed electrical power. The goal of the DARPA High Energy-Density Power Program is to develop and demonstrate replacement power sources for numerous military applications. One effort, being run in collaboration with the Army Research Office, has demonstrated a prototype fuel cell designed to replace in many applications a popular military standard battery. The target application is the Army's BA-5590 primary (i.e., use-once-and-dispose) lithium battery... These new fuel cells, on the other hand, are not thrown away after each use but can be reused hundreds of times. Mission weight savings of factors of 10 or more are projected. The prototype fuel cell, which has the same size and delivers the same power as a battery, has been tested in all orientations and under simulated adverse weather conditions, and was enthusiastically received by Army senior management. We plan future field trials.
>
> In the future, DARPA is developing even higher energy-density power systems based on a number of novel concepts including the direct oxidation of methanol as a fuel, the development of micro (centimeter-sized) turbines and thermophotovoltaics. Ultimately, one would like to be able to harvest energy from the environment so that one would never need to replace a battery. DARPA is exploring concepts in this area as well, as discussed below.
>
> Technology Push focuses on the identification of key technologies which are believed to have strong potential for military applications. DARPA is investing in several basic technology development projects that offer tremendous potential -- even revolutionary -- benefit to the military services. Consider, for instance, developing the technology that enables the warfighter to derive his operational energy requirements from his

> environment… By judiciously withdrawing energy where it has been banked over time from low-level sources available environmentally, one moves quickly to a revolutionary vision of warfare. This is clearly out of reach today, but the long-term military benefits warrant its exploration. DARPA will pursue the technologies which might enable this and other such visionary capabilities.[87]

Mr Lynn's testimony shows the direction the DoD has been heading with respect to renewable power sources for at least the past seven years. It has been established that disposable batteries are no longer tenable on their own – the DoD has established a need for renewable power sources, and is searching for the ideal combination that will fulfill that need, while simultaneously increasing performance and reducing total life cycle costs.

B. ADVANTAGES OF USING RECHARGEABLE BATTERIES OVER DISPOSABLE

There are many advantages inherent in the use of rechargeable batteries compared to disposable batteries. It is generally accepted that total costs over the life cycle of any battery powered system are lower when using rechargeable batteries. These cost reductions are manifested in both lower battery acquisition costs as well as reduced transportation and handling costs. The 2nd Battalion, 502nd Infantry Regiment, 101st Airborne Division (Air Assault) from Fort Campbell, Kentucky conducted a feasibility study for the best battery purchase plan and determined that rechargeable batteries yielded cost and flexibility advantages.[88] Also, the 3rd Battalion, 504th Parachute Infantry Regiment, 82nd Airborne Division from Fort Bragg, North Carolina estimated it saved $665,790 during its six month peacekeeping mission in Kosovo due to switching to rechargeable batteries.[89]

87 http://www.defenselink.mil/speeches/1997/t19970311-lynn.html, 24 September 04

88 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 5

89 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 5

1. Cost Analysis of PVPCT Incorporation

To conduct this analysis, some assumptions have been made. First, the assumption of the "standard rechargeable battery load" which provides prolonged operations for a specific piece of equipment. For this assumption, each piece of powered equipment requires three things for indefinite operations: four rechargeable batteries (assuming parallel (2 battery) system and 24 hour operations – two batteries in the equipment, one battery being charged, and one battery awaiting installation), one PVPCT controller, and one solar collector array. (Note: this analysis focuses on the first time use – the conversion to the new technology. Costs for subsequent missions do not include these costs as the equipment is reusable. A "second mission" analysis using equipment purchased in a previous mission will show incredibly low costs.) Table 1 below shows the cost of such a system:

4 x BB-2590 Rechargeable Batteries	$1320
PVPCT Controller	$500
Solar Array	$358
Transportation to Kuwait	$51
Total Cost	$2229

Table 1. Estimated Cost Components for One PVPCT System

Shipping costs are estimated at approximately $39 for four BB-2590s and $12 for the PVPCT controller and solar array, at a combined weight of four pounds. Using BB-2590 batteries, one PVPCT system provides 1200 charge cycles, or about 36,000 operational hours in an AN/PRC-119 under normal operating conditions. Under the same operating conditions, 36,000 operational hours for an AN/PRC-119 requires about 1500 BA-5590s, or roughly three-quarters of a pallet. The costs associated with 1500 BA-5590s are $160,500 for acquisition and disposal and $14,490 for transportation to Kuwait, totaling $174,990. The difference in the cost between these two scenarios favors the PVPCT system by $172,761 per AN/PRC-119 for every 36,000 operational hours – about 4.1 years of constant operations. These cost estimates do not include costs associated with inventory carrying costs for either battery, which are significantly higher

with the BA-5590 due to greater volume. They also do not include transportation costs associated with the last tactical mile – i.e. from the port of entry in Kuwait to the end consumer.

Figure 19 compares costs of all rechargeable batteries to the disposable BA-5590 based on operational hours. These costs include acquisition and logistic costs minus transportation. This figure shows that the break even point for units switching from disposable batteries to PVPCT with the BB-2590 occurs at 220 operational hours, ($2184.00 total cost per system).

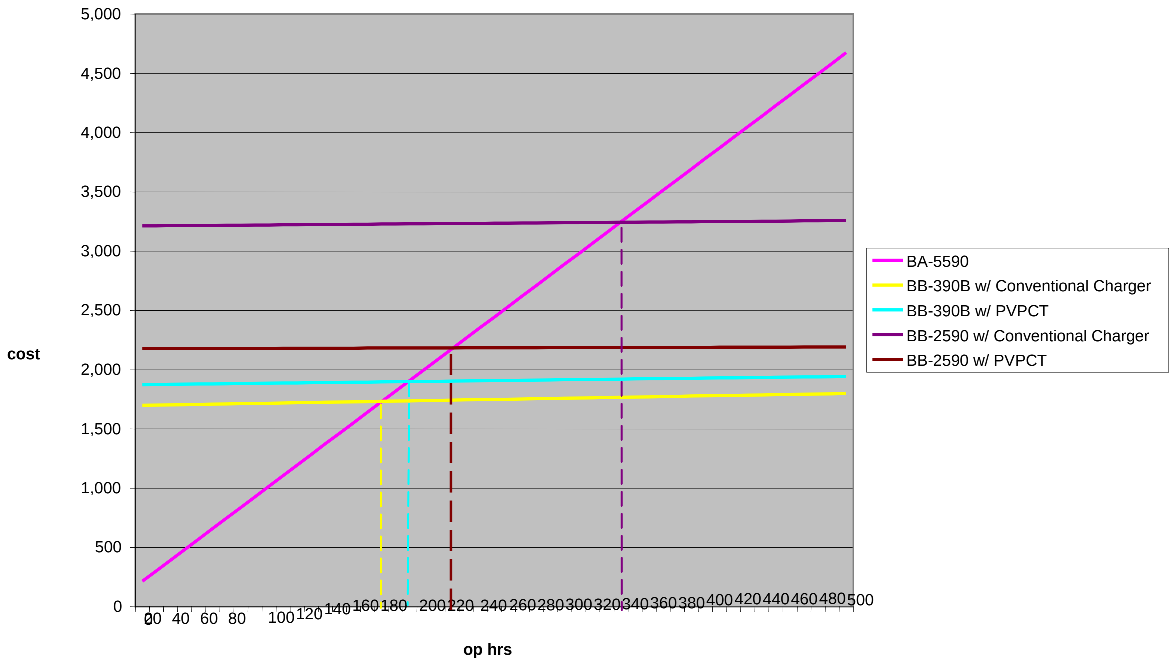

Figure 19. Comparative Cost v. Operating Hours

Figure 20 provides a break even analysis between the various rechargeable battery types and PVPCT use. This chart shows that over time, the systems utilizing PVPCT reduce total life cycle costs. At 3,000 operating hours, the BB-2590 with PVPCT becomes the most cost effective option, at $2,288.00 per powered system. The figures incorporate a utilities cost of $.0625 per hour for fuel or commercial power for systems requiring a conventional charger – this assumes a typical tactical generator burns approximately 6 gallons of diesel fuel per hour to produce 60kW and assumes a rough estimate of $1.66 per gallon, which equates to $10 of diesel per hour per generator. This

further assumes that each 60kW generator could charge four PP-8498 chargers in 8 hours, a total of 32 batteries, yielding 1,280 operational hours (32 times 40 hours each). $80.00 in fuel divided by 1,280 operational hours equals $.0625 in fuel cost per operational hour.

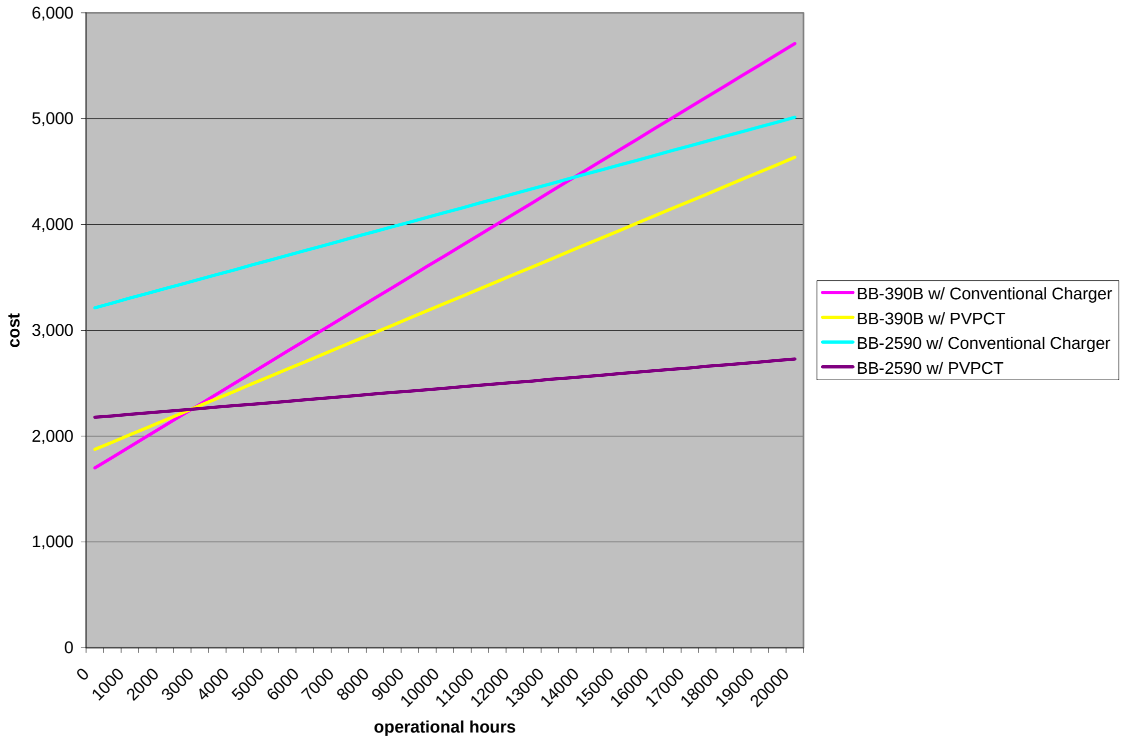

Figure 20. Break Even Analysis Between Rechargeable Systems

Another advantage that disposable batteries offer is reduced disposal costs – this can be partly attributed to the fact that rechargeable batteries last longer and are discarded less frequently. One example of this is the AN/PRC-119 radio -- the Army has determined it can save $417 in disposal costs per radio over a three year period just by switching to rechargeable batteries.[90] The other disposal-related economy deals with the chemical composition of rechargeable batteries compared to disposable batteries. BA-5590s are composed of Lithium Sulphur Dioxide, which is considered to be hazardous material and requires special handling and disposal procedures.[91] Rechargeable batteries, on the other hand, are typically composed of either Nickel Metal Hydride or Lithium Ion,

90 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 5

91 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 5

neither of which are generally considered to be hazardous materials.[92] This makes the planning and logistics involved with rechargeable batteries considerably easier. "Packing (for deployment in Kosovo) was noticeably easier because the BB series (of rechargeable) batteries are not hazardous material and no special paperwork or packing was required."[93]

2. Weight Analysis of PVPCT Incorporation

The analysis of weight provided in this section is from the perspective of the using unit. In particular, the purpose of this portion of analysis is to contrast the weight that individual soldiers and small units would have to bear to power their systems in different scenarios when removed from their logistics re-supply for a prolonged period.

Weight for the PVPCT system, broken down by major component is shown in Table 2:

4 x BB-2590	12.8 lbs
PVPCT Controller	~1 lbs
Solar Array	3 lbs
Total	**~16.8 lbs**

Table 2. Weight of the PVPCT System by Major Component

For the disposable system, the weight is 4.6 pounds for two BA-5590s at any given time. When considering a snapshot in time, the weight comparison here favors the disposable system by over 12 pounds. In light of this, it is important to note that in order to provide operational capability over a prolonged period (i.e. 36,000 operational hours), the logistics system has to transport and handle 1,500 BA-5590s, a total weight of 3,450 lbs per system, compared to the 16.8 lbs associated with the four BB-2590s. To more fully illustrate these dynamics, the following scenarios are considered.

92 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 5

93 Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Forces, pg. 3

a. Short Duration Missions

The PVPCT's primary utility is found in the protracted mission arena. Missions that are of a short duration, those that do not require the changing of batteries in any powered gear, do not realize any significant utility from adopting the PVPCT. In this case, each piece of powered equipment requires twice its operational battery load – one for operations and one as a spare. This means that the typical one battery radio requires 4.6 lbs of disposable batteries (two BA-5590s). PVPCT and the solar array are not carried in this scenario – there is no reason to deploy it to recharge batteries, so it is excess weight. Therefore, it appears that adopting PVPCT adds no value to this category of mission. However, if the PVPCT charging technology is used in a home base model, the rechargeable battery can be carried as easily as the disposable. The economic savings justify the use of rechargeable batteries even for short duration missions.

b. Remote Medium- and Long-duration Missions

For the purpose of the weight analysis, these missions are defined as scenarios where the detached unit is away from logistic infrastructure for a sufficient duration to require changing batteries in powered equipment, meaning they are required to carry their own replacement batteries for the entire mission.

To best analyze the economies gained by PVPCT, we start by analyzing specific types of battery-powered equipment items and the associated weight of their battery requirements. The assumption driving this analysis is that the powered equipment is constantly operating, resulting in maximum drain on the batteries. Since BA-5590s do not have state-of-charge indicators, this is the typical method used in determining the frequency of their replacement. For example, it is the standard operating procedure for many operational units to replace the BA-5590s in their AN/PRC-119 family of radios every 24 hours, regardless of how many hours the radios were actually powered during that period. The calculated number of batteries required in this analysis includes both in-use batteries and spares, calculated at a 90% service level assuming normal distribution – i.e., the system has extra batteries to ensure that at least 90% of the time it has the power to function as needed. Figure 21 shows the comparative weight analysis for a system that

consumes one BA-5590 in a 24 hour period. An example of this type of equipment is the AN/PRC-119 family of radios.

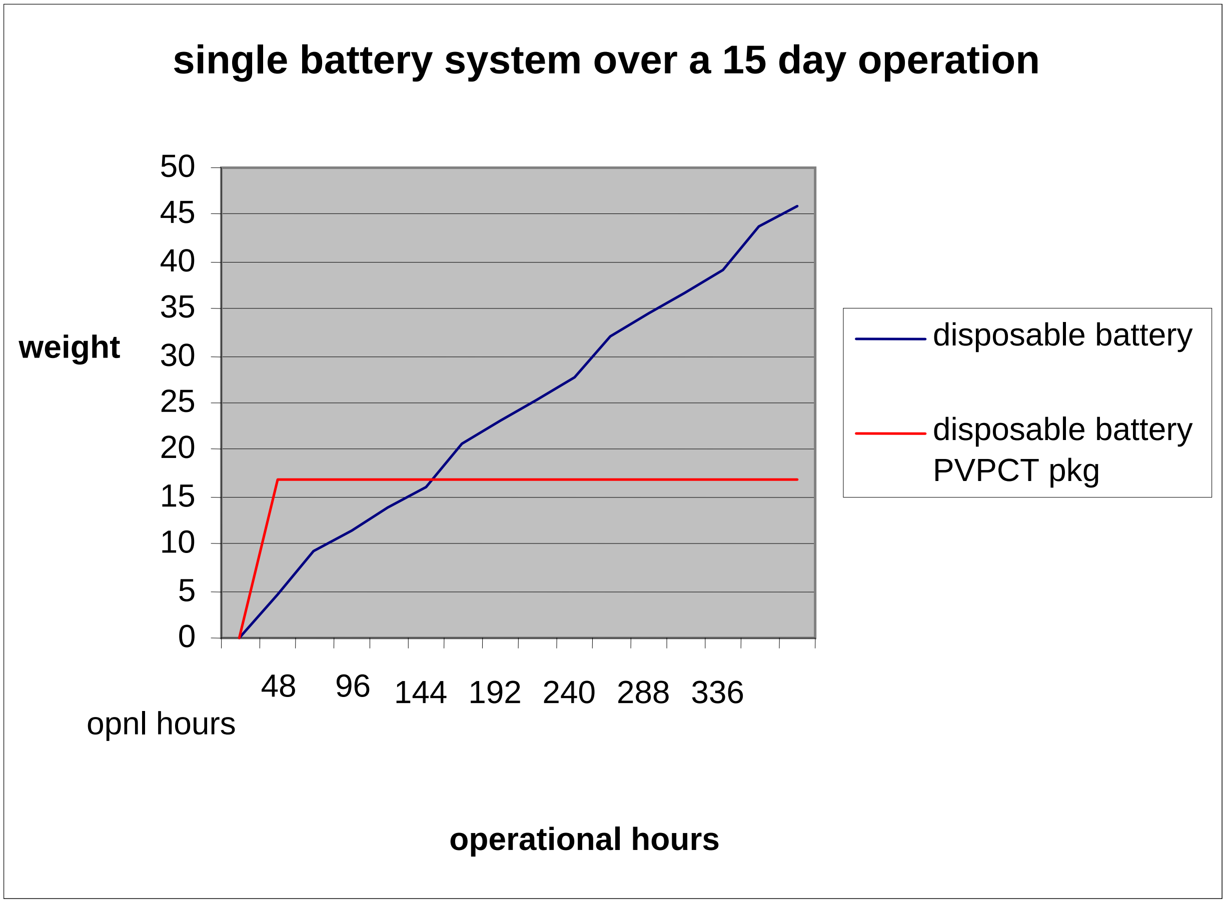

Figure 21. Battery Weight Comparison for a Single Battery System

As Figure 21 indicates, by switching from disposable batteries to a PVPCT charging system, this type of equipment realizes a weight economy after the 120th hour of operations without re-supply.

Figure 22 depicts the same metric for a dual battery system. Examples of the dual battery systems include the AN/PRC-117, AN/PRC-150, and the AN/PSC-5 radios.

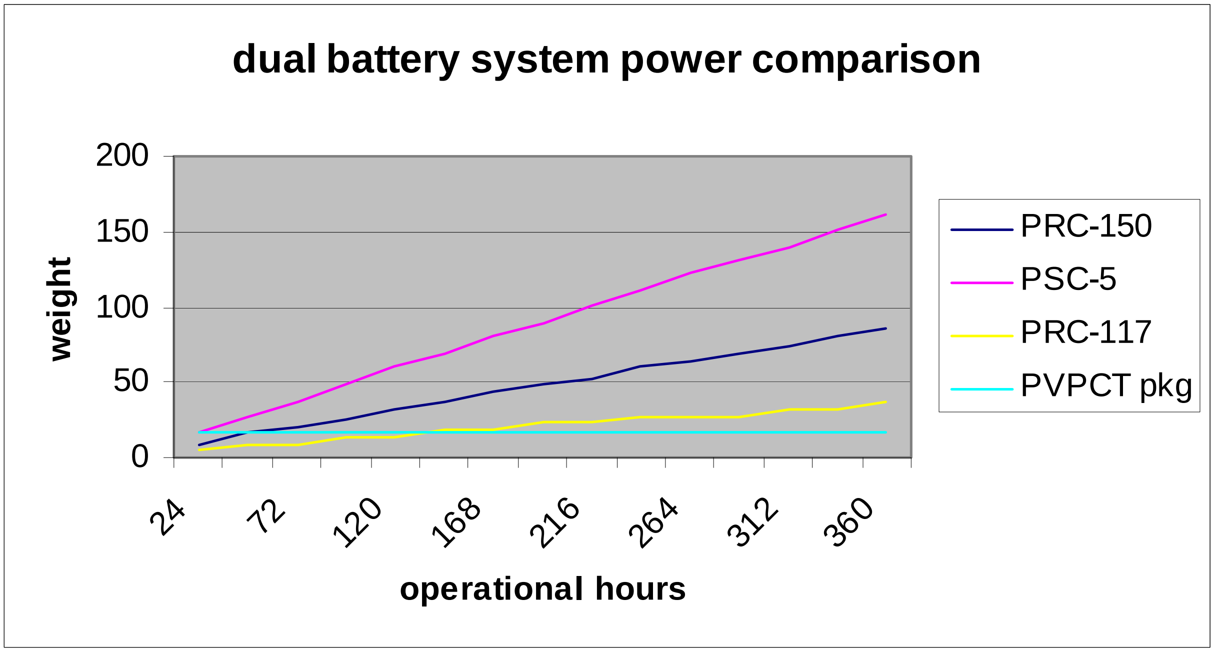

Figure 22. Battery Weight Comparison for a Dual Battery System

The AN/PSC-5 consumes a set of batteries after approximately 12 hours of operation, the AN/PRC-150 uses a set of batteries in about 24 hours, and the AN/PRC-117 consumes a set of batteries after about 36 operating hours.[94] Figure 22 indicates that by incorporating PVPCT, the AN/PSC-5, AN/PRC-150, and AN/PRC-117 realize weight economy after 24, 48, and 144 hours of operations, respectively, without re-supply.[95] Note that the PVPCT package is a flat line regardless of the dual battery system supported. As long as the cycle time (i.e. battery discharge time) is greater than the battery charge time – approximately eight hours per PVPCT system under ideal conditions – the system composition remains the same: four BB2590s, the controller, and the solar array. For these scenarios, the PVPCT charging system is defined as four BB-2590 batteries, one controller, and one Iowa Thin Films R-15-1200 solar array.

Figure 23 indicates the weight comparison for a system with a higher power drain rate – the SOFLAM laser marker system. This system, which requires five BA-

94 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pp. C-7 – C-49.

95 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pp. C-7 – C-49.

5590s for every six hours of constant operations, requires a different PVPCT system than that defined above. For the analysis of this system, we assume that batteries are changed every 24 hours. SOFLAMs are not in constant use on the battlefield. While each set of batteries provides nearly six hours of designation time, the lack of a state-of-charge indicator leads to a reasonable policy of changing these batteries every 24 hours. For this scenario, a PVPCT system must consist of 13 BB-2590s - five in the equipment, five in the charger, three spares; five PVPCT controllers and five Iowa Thin Films R-15-1200 solar arrays. This system weighs a total of 70.7 pounds and provides indefinite operation of the SOFLAM. By comparison, 70.7 pounds of BA-5590s, or approximately 30 batteries, provides 36 hours of lasing in the SOFLAM.[96]

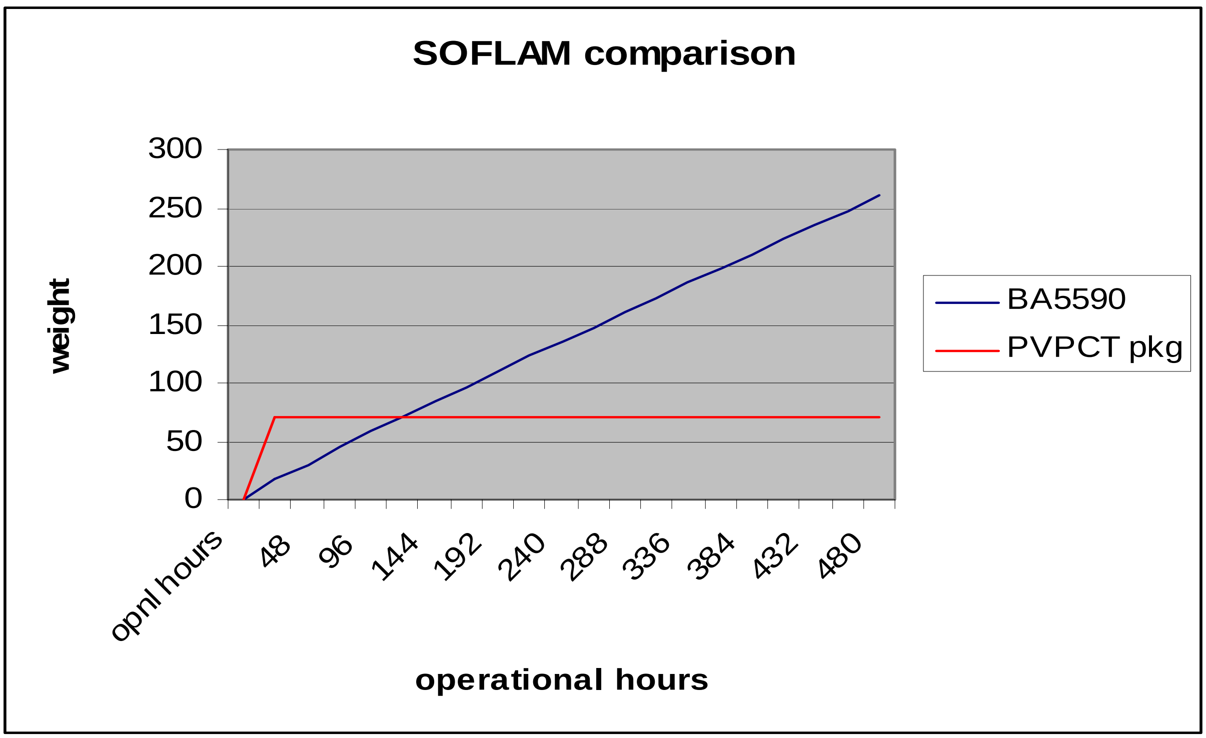

Figure 23. Battery Weight Requirements for the SOFLAM

96 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pp. C-7 – C-49.

Figure 23 shows that for this type of system with high battery requirements, the PVPCT offers greater weight economy after 120 hours of operation, providing that BA-5590s are changed every 24 hours, regardless of usage rate.

For both of these remote mission categories, current battery re-supply is typically performed via helicopter or truck. The high cost and limited availability associated with these assets often results in surplus spares having to be carried by supported units. By switching to the PVPCT, these units greatly reduce their combat load as well as their frequency of re-supply missions using these high demand transportation assets. By reducing their combat load, the individual soldier then has an increased capacity for food, water, ammunition, or other various supplies. By reducing the demand for high value transportation assets, these assets can be more productively utilized in other endeavors, such as MEDEVAC missions, assault support missions, and focusing on the re-supply of ammunition, fuel, medicine or other critical supplies, as well as attaining greater availability for the support of various other units.

The scenarios outlined above are in general terms. A more granular analysis regarding specific battery statistics and consumption rates based on more detailed mission profiles are addressed later in this chapter.

C. ANALYSIS OF THE U.S. MARINE CORPS OVERARCHING BATTERY STUDY REQUIREMENTS DETERMINATION FORMULA

In February 2004, Marine Corps Systems Command completed an overarching service-wide battery study. As an update to the *Battery Support to the Fleet Marine Force* study completed in February 1996, the objective of the more recent study was "to update the Marine Corps' battery consuming equipment data and to develop a computer model to assist the users in determining the battery requirements across a spectrum of exercises, scenarios, and operating environments."[97] The battery study was divided into five major tasks:

97 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pg. ES-1

(1) Identify all principle end items used by the Marine Corps that require batteries

(2) Identify the quantity of each principle end item possessed by the Marine Corps

(3) Recommend specific battery types and amounts

(4) Develop a methodology to estimate battery consumption rates

(5) Develop a model to predict battery usage[98]

Each major task incorporated in the battery study was geared toward the final task – the development of the computer model to allow unit commanders to predict battery requirements for virtually any deployment, operation, or exercise. The 1996 Battery Study to Support the Fleet Marine Force was used to initially populate the list of Marine Corps principle end items that require batteries. Research of Marine Corps programs from 1996 to 2004 was conducted to complete the list. Usage, consumption, and environmental data was gathered from technical manuals, stocklists, government and commercial websites, as well as other sources for the principle end items identified in task one. Formulas identified from task four were then used to derive consumption rates based on the data gathered.[99]

The Master Battery Requirements Model developed as a result of task five uses Microsoft Access in a decision engineering-designed database. The model is meant to be used at the tactical, operational, and strategic levels to assist Marines in the field, as well as managers at the Headquarters, Marine Corps level to efficiently determine battery requirements. In their development effort, the study team found that the United States Army Communications-Electronics Command was independently developing a battery planning model in parallel with the United States Marine Corps model. The main

98 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pg. I-3

99 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pg. I-5

difference between the two models is that the model developed by the army is designed for top-level use only and is not meant to be implemented at the field level.[100]

The model developed for the Marine Corps study helps using units determine how many batteries of all types they need for a particular evolution and is the method we use in the next section to determine battery requirements for each scenario. It was developed in an effort to help using units facilitate the transition from rechargeable to disposable batteries. The model is based on a series of equations that account for equipment types and quantities, battery types and quantities, duration of operations, as well as the operating environment.[101]

The screen capture of the computer model conveys its simplicity. In order to determine battery requirements for a particular evolution, the user needs to input seven pieces of information:

(1) The number of days the unit will be deployed

(2) The number of days the unit will be operational while deployed

(3) The general climactic conditions where the unit will be operating

(4) The types of equipment items to be used

(5) The quantity of each equipment type

(6) An estimate of the average operating hours per day for each equipment item type

(7) Whether or not battery chargers will be available for the batteries required for each equipment type

All other information is either optional or contains a default value that was determined by the study group to represent the "best guess" value if the precise value is not known or cannot be estimated.

100 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pg. II-18

101 Marine Corps Systems Command (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pg. I-5

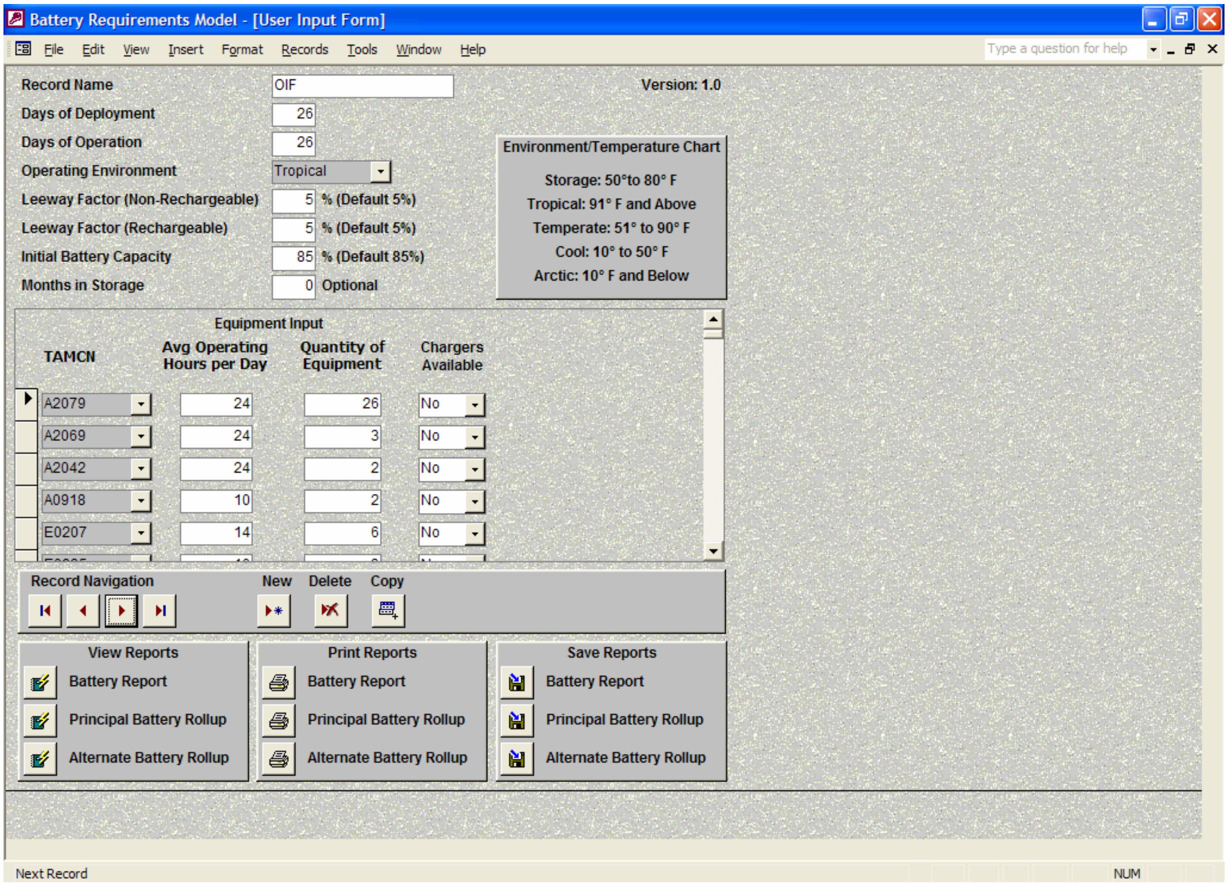

Figure 24. USMC Battery Model Screen Capture

Once the required information is input, the model returns a report that lists the quantities of each battery type that are required for each equipment item type. If the user indicates that conventional battery chargers are available, the report indicates the number of both disposable and rechargeable batteries that the unit requires.

D. ILLUSTRATIVE SCENARIOS

As stated in Chapter III, the utility of incorporating PVPC technology is demonstrated through three illustrative scenarios: a Marine Corps Combined Arms Exercise, support and stability operations, and high-intensity combat operations. The analysis for each scenario is centered on an infantry battalion and the attached units specific to each scenario. For each scenario, we take into account the duration of the scenario, the equipment requirements, logistical support available, and the supporting arms employed. The level of logistical support is considered a key driver for using unit

battery carrying requirements. The more robust the logistical support, the fewer batteries the using unit requires. Additionally, supporting arms are considered to be a key driver for battery requirements since the employment of more supporting arms such as artillery and close air support requires the use of a greater quantity and variety of communications assets.

For the notional infantry battalion, 50 PVPCT systems are assumed to be included on the table of equipment: fifteen total assigned to the radio operators within the rifle companies, six assigned to the artillery forward observers normally attached to each company, four assigned to the forward air controllers, three assigned to the 81mm mortar forward observers, six assigned to the heavy machine gun teams, six assigned to the Javelin teams, and ten for spares. Spares are calculated using a normal distribution of failures and ensuring a 95% service level. The initial acquisition cost to outfit this battalion with PVPCT systems, including solar arrays and converters, calculated previously in this chapter at approximately $850 each is $42,500. The initial systems, including the batteries, are purchased through the acquisition process using procurement funds and cost nothing to the using unit; therefore, in the analysis of the following scenarios initial acquisition cost is not included.

1. Combined Arms Exercise

Marine Corps combined arms exercises (CAXs) are conducted at the Marine Air-Ground Task Force Training Center (MAGTFTC), located in the Mojave Desert at 29 Palms, California. Each CAX lasts three weeks and culminates with a final exercise, or FINEX, involving the entire battalion. Between evolutions, units have access to Camp Wilson, a forward support base located on MAGTFTC that boasts robust logistical support capabilities. Over the course of the exercise, the battalion interfaces with fixed-wing and rotary-wing close air support assets as well as an artillery battalion. Forward air controllers attached to the infantry battalion communicate with close air support assets using the AN/PRC-117F UHF radio. Communications with the artillery battalion are conducted via the AN/PRC-119 VHF family of radios for short-haul communications and the AN/PRC-150 HF radio for long-haul communications. Table 3 shows the evolutions

that take place over the course of a CAX, the equipment items involved that require BA-5590s, and the pertinent battery usage data for each equipment item:

Evolution	Unit Size	Duration (T_o)	Number of Runs	Equipment Requiring BA-5590 or Equivalent (Z)	Batteries per Equipment Item ($M_{b,e}$)	Quantity of Equipment Item per Run (Q_e)	Duty Cycle (D_e)
Range 400	Platoon	1 Day	9	AN/PRC-119	1	1	0.3
Mobile Assualt Course	Company	1 Day	2	AN/PRC-119	1	9	1
				AN/PRC-117	2	1	0.6
				M98A1 Javelin	2	2	0.167
				GLTD II	5	2	0.2
Helicopter-borne Assault Course	Company	1 Day	1	AN/PRC-119	1	9	1
				AN/PRC-117	2	2	0.8
				M98A1 Javelin	2	2	0.167
				GLTD II	5	2	0.2
Fire Support Coordination Exercise I	Battalion CP and Company Fire Support Teams	1 Day	1	AN/PRC-119	1	15	1
				AN/PRC-117	2	3	0.75
				AN/PRC-150	2	2	1
				GLTD II	5	6	0.2
Fire Support Coordination Exercise II	Battalion CP and Company Fire Support Teams	2 Days	1	AN/PRC-119	1	15	1
				AN/PRC-117	2	3	0.75
				AN/PRC-150	2	2	1
				GLTD II	5	6	0.2
Air Support Coordination Exercise	Battalion CP and Company Fire Support Teams	1 Day	1	AN/PRC-119	1	15	1
				AN/PRC-117	2	3	0.75
				AN/PRC-150	2	2	1
				GLTD II	5	6	0.2
Final Exercise	Reinforced Battalion	3 Days	1	AN/PRC-119	1	26	1
				AN/PRC-117	2	3	0.6
				AN/PRC-150	2	2	1
				M98A1 Javelin	2	6	0.167
				M220E4 TOW	4	3	0.25
				GLTD II	5	6	0.2
				SOFLAM	5	3	0.2
				AN/UAS-12C	4	3	0.125

Table 3. CAX Evolutions and Pertinent Battery Usage Data

Inputting the data into the battery formula described in section C of this chapter, the following battery requirements for a combined arms exercise are calculated:

Evolution	Number of Runs	BA-5590 Requirement Per Run	BA-5590 Cost Per Run	BA-5590 Weight (lbs) per Run
Range 400	9	1	$107	2.3
Mobile Assault Course	2	28	$2,996	64.4
Helicopter-borne Assault Course	1	28	$2,996	64.4
Fire Support Coordination Exercise I	1	64	$6,848	147.2
Fire Support Coordination Exercise II	1	129	$13,803	296.7
Air Support Coordination Exercise	1	64	$6,848	147.2
Final Exercise	1	336	$35,952	772.8

Total BA-5590s Required	686
Total BA-5590 Cost	$ 73,402
Total BA-5590 Weight (lbs)	1577.8

Table 4. Combined Arms Exercise BA-5590 Requirements

The analysis shows that the use of disposable batteries costs the Marine Corps about $73,000 per CAX. While this number may seem relatively negligible in comparison to the overall Marine Corps budget, this amount becomes more significant considering that the Marine Corps runs ten combined arms exercises every fiscal year.[102] Considering that the Marine Corps conducts a number of other exercises of similar duration and scope every year, such as Tandem Thrust, Foal Eagle, Cobra Gold, Ulchi Focus Lens, Desert Fire Exercises, and Steel Knight[103], the savings that can be realized through the replacement of BA-5590s alone with rechargeable systems is remarkable.

The utility of using the PVPCT system in training exercises such as those listed above, though, bears further analysis. As discussed in section C of this chapter, PVPCT bears the greatest utility in operations of long duration, wherein the using unit is not located in close proximity to a robust supporting structure. For the major exercises cited, including CAX, the units involved typically operate within short reach of their supporting

102 Hanlon, LtGen E. J., MCO 3500.11E: Marine Corps Combined Arms Exercise (CAX) Program, signed 21 November 2001, pg. 3

103 Headquarters, Marine Corps Programs and Resources Department (2000). *United States Marine Corps Concepts & Issues 2000: Leading the Pack in a New Era*, Washington, D.C.: U.S. Government Printing Office, pg. 96

logistics units. Additionally, the duration of these exercises are known, unlike the two following scenarios. Thus, commanders can accurately plan for and tightly control their battery requirements and usage. In such situations, commanders have the luxury of devising and monitoring a rechargeable battery rotation plan. Also, even in major exercises, commanders know that if supplies run short, timelines can be adjusted to a degree in order to take whatever corrective actions are necessary. Though these exercises clearly favor the use of rechargeable batteries, at least from a service-wide fiscal standpoint, current rechargeable technology is probably sufficient.

2. Stability and Support Operations

The typical infantry battalion in Iraq or Afghanistan participates in a spectrum of activities classified as stability and support operations. These operations can run the gamut in terms of the size of the unit involved, their duration, and supporting arms employed. For support and stability operations, especially those conducted in an urban environment, the Marine Corps instructs its leaders at all levels on the concept of the "three block war." According to this concept, in the space of three city blocks a unit may be involved in humanitarian operations on one block, controlling an unruly mob and perhaps dealing with sporadic gunfire on the next, and engaged in a fire fight with a well-armed and well-organized enemy on the third block. The concept of the three block war introduces a consideration visited throughout the remainder of this discussion: that of uncertainty.[104]

Though many factors concerning stability and support operations may vary, it is assumed that throughout such operations, there is some kind of access to a robust support infrastructure available to the frontline combat units. That access may be via overland convoy or helicopter-borne re-supply, but under such operations, the commander can be sure that supplies will come from a well-stocked supply base. Table 5 shows five representative combat mission types that might be conducted during stability and support operations, the equipment items involved that require BA-5590s, the re-supply available for each mission, and the pertinent battery usage data. The missions shown were meant to represent various levels of units involved from the battalion level and below, various

104 http://www.nyu.edu/globalbeat/syndicate/burgess102803.html, 28 September 04

mission durations, and various means of re-supply available. The column "Re-Supply Available" represents the expected support the unit involved requires during the duration of the mission.

Evolution	Unit Size	Re-Supply Available	Duration (T_o)	Equipment Requiring BA-5590 or Equivalent (Z)	Batteries per Equipment Item ($M_{b,e}$)	Quantity of Equipment Item per Run (Q_e)	Duty Cycle (D_e)
Urban Patrol	Platoon	None	0.25 Days	AN/PRC-119	1	1	0.3
Long-Range Reconnaisance Patrol	Recon Team (4 Marines / Soldiers)	None	14 Days	AN/PRC-119	1	26	1
				AN/PRC-117	2	3	0.6
				AN/PSC-5	2	2	0.25
				GLTD II	5	6	0.1
Raid	Company	None	1 Day	AN/PRC-119	1	26	1
				AN/PRC-117	2	3	0.3
				M98A1 Javelin	2	6	0.2
				GLTD II	5	6	0.2
Tora Bora - Operation Anaconda	Reinforced Battalion	On-call, via helicopter	30 Days	AN/PRC-119	1	26	1
				AN/PRC-117	2	3	0.6
				AN/PRC-150	2	2	1
				AN/PSC-5	2	2	0.25
				M98A1 Javelin	2	6	0.2
				GLTD II	5	6	0.2
				SOFLAM	5	3	0.2
				AN/UAS-12C	4	3	0.25
Battle of Najaf	Reinforced Battalion	On-call, via overland convoy	30 Days	AN/PRC-119	1	23	1
				AN/PRC-117	2	3	0.6
				M98A1 Javelin	2	6	0.2
				M220E4 TOW	4	3	0.25
				GLTD II	5	6	0.2
				SOFLAM	5	3	0.2
				AN/UAS-12C	4	3	0.25

Table 5. Stability and support Operations Missions and Battery Usage Data

Utilizing the battery requirements formula described in section C of this chapter, the following battery requirements for support and stability operations are calculated:

Mission	BA-5590 Requirement	BA-5590 Cost	BA-5590 Weight (lbs)
Urban Patrol	1	$107	2.3
LRRP	176	$18,832	404.8
Raid	25	$2,675	57.5
Tora Bora	3404	$364,228	7829.2
Battle of Najaf	3040	$325,280	6992

Table 6. BA-5590 Requirements for Stability and Support Operations Missions

It is in the area of stability and support operations that the decision to use disposable batteries or rechargeable batteries is perhaps the most critical. As shown in section B, it is in missions of medium- to long-duration, wherein the units involved are located at a great distance from their supporting infrastructure, that PVPCT realizes its greatest utility. The spectrum of missions conducted under stability and support operations straddle this threshold of utility.

The numbers show that missions like Operation Anaconda and the Battle of Najaf incur similar requirements for BA-5590s. In situations like Operation Anaconda, the choice of whether or not to use PVPCT is clear. The mission was of long duration and re-supply was tenuous at best, utilizing vital air assets and exposing these assets to hostile fire in the process. As such, it was of vital importance that combat commanders limit their re-supply requests. The utilization of a renewable power capability, such as PVPCT would have greatly aided commanders in this respect. The use of PVPCT in Operation Anaconda would have meant fewer re-supply missions and, on those re-supply missions that were conducted, more space on the helicopters for other necessities.

In situations like the Battle of Najaf, the choice is even clearer. Although it was an operation conducted in close proximity to a robust support structure, front-line units could expect a 36 hour lag between when a supply request was transmitted to the time that supplies were received.[105] Additionally, supply convoys faced the real possibility of ambushes and attacks via improvised explosive devices during their missions between their supply bases and the supported units. The dynamic and uncertain nature of the battle made it unclear as to whether or not a disciplined battery rotation plan could be used. Having an internal, independent charging system such as the PVPCT would have been extremely valuable.

At the beginning of this subsection, the concept of the three block war was discussed. The implication of this concept on logistics planning and execution to the combat commander seems to be that more care than ever before must be taken when planning equipment loads for any particular mission. During the Battle of Somalia, the Rangers that executed the raid on the Olympic Hotel did not take their night vision

105 www.centcom.mil/CENTCOMNews/Stories/09_04/28.htm, 28 September 04

goggles along with them because they only expected the mission to last about one hour.[106] Even if they had, there would have been no batteries to operate them beyond their expectation of the mission duration. Similarly, the Battle of Najaf began with a few American troops reinforcing Iraqi police when their stations in that city came under attack from insurgents. Once it became clear that the fight was going to be much more intense than anticipated, further reinforcements were rushed to Najaf without all of the critical supplies they knew they would need.[107] The unit commanders for the initial troops sent into Najaf could not have known that their mission would turn into a month-long protracted battle. In section B of this chapter, we established that for a single battery system, such as an AN/PRC-119, the break-even point for weight for switching from disposable to rechargeable batteries comes at the 120th hour of operations. In order to optimize the battery load of his troops, the unit commander for the initial troops sent to Najaf would have had to anticipate that the mission would last at least five days. Again, having an integrated charging capability, even if the mission is not expected to last beyond a couple of days, is a critical force multiplier.

As stated above, the concept of the three block war seems to indicate that commanders must take greater care with logistics planning and execution, whether that means taking every equipment item that might conceivably be needed under any circumstance during the mission, or planning for the on-call delivery of these items when needed. One might argue that another implication of the three block war concept, though, is that troops need equipment that eases the burden of detailed logistics planning and execution. In light of this, it seems that PVPCT is particularly well-suited to deal with the uncertain nature of urban stability and support operations. Essentially, PVPCT turns what was once a consumable item into a durable item.

3. High Intensity Combat Operations

For the purpose of this analysis, the invasion of Iraq during Operation Iraqi Freedom is used as the template for a high-intensity combat operation. For a battalion-

---

106 Bowden, Mark, *Blackhawk Down; A Story of Modern War*, New American Library, NY, 1999, pg. 44

107 www.centcom.mil/CENTCOMNews/Stories/09_04/28.htm, 28 September 04

sized unit, it can be reasonably assumed that the entire battalion is involved in operations at any particular time. The battalion is expected to employ virtually every one of its assets at some point in such an operation and be required to utilize the entire spectrum of supporting arms. Table 7 shows the battalion-level equipment items requiring BA-5590s involved in such a high-intensity combat operation and the associated battery usage data for these equipment items:

Unit Size	Re-Supply Available	Duration (T_o)	Equipment Requiring BA-5590 or Equivalent (Z)	Batteries per Equipment Item ($M_{b,e}$)	Quantity of Equipment Item (Q_e)	Duty Cycle (D_e)	BA-5590 Requirement
Reinforced Battalion	Limited	26 Days	AN/PRC-119	1	26	1	626
			AN/PRC-117	2	3	1	356
			AN/PRC-150	2	2	1	87
			AN/PSC-5	2	2	0.4	108
			M98A1 Javelin	2	6	0.6	1350
			M220E4 TOW	4	3	0.4	386
			GLTD II	5	6	0.3	1333
			SOFLAM	5	3	0.2	417
			AN/UAS-12C	4	3	0.3	310
			M22 Chemical Agent Alarm	2	30	1	1446

BA-5590 Quantity		6,419
BA-5590 Cost	$	686,833
BA-5590 Weight		14,763.7

Table 7. Battalion-Level Equipment Items Requiring BA-5590s During OIF

In the Operation Iraqi Freedom after-action reports, many of the ground units included comments addressing the difficulty of executing re-supply missions, especially with respect to keeping front-line troops supplied with an adequate amount of batteries. The 3rd Infantry Division's lessons learned report states, "Battery resupplies [sic] were isolated events and barely sustained units through the transition to stability and support operations."[108] A Marine Corps Systems Command analysis of Operation Iraqi Freedom found that, "With the obvious shortage of BA-5590s the Marines were asking for <u>more alternative sources of power</u>." (Emphasis in original text)[109]

108 Third Infantry Division (Mechanized) After Action Report: Operation Iraqi Freedom, pg. 196

109 Field Report, Marine Corps Systems Command Liaison Team, 20-25 April 2003, pg. 7

Re-supply missions were hampered by the speed and doctrine of the attacking forces. Not only did the speed of the advance result in extraordinarily extended supply lines, but the fact that the main combat units purposely bypassed many enemy units in the rush toward Baghdad meant that supply convoys were forced to drive through unsecured territory. The ambush of the 507th Ordnance Maintenance Company on March 23, 2003 in the town of An-Nasiriyah, which resulted in the media sensation surrounding the capture and subsequent rescue of Private First Class Jessica Lynch, highlighted this predicament. According to Colonel Mike Hiemstra, of the Center for Army Lessons Learned, in an interview with Jane's Defence Weekly conducted only a few days after the fall of Baghdad, "Supply line attacks have already resulted in changes in the field, with supply units limiting the size of convoys to keep command and control intact."[110] Smaller convoys mean that combat commanders must make hard choices when balancing requests for ammunition, food, water, and batteries. Such changes in doctrine lend themselves to equipping front-line troops with the capability to recharge their own batteries, which requires less frequent and smaller re-supply missions to keep them provisioned.

E. PVPCT'S NICHE MARKET

As noted above, the use of rechargeable batteries can be broken into two categories – when co-located with, or near, a robust logistics infrastructure and when no logistics infrastructure is readily available. When there is ready access to a robust logistics infrastructure, to include buildings with house power, compounds with tactical generator support, or areas with ready access to vehicles, the use of rechargeable batteries becomes elementary – there are sufficient assets to power conventional recharging units. Economies gained from the implementation of PVPCT in these units are not realized until further in the life cycle, as shown in Figure 20; however, there has long been a capability gap for those forces that have battery requirements and do not have access to a robust supporting infrastructure. Historically, it has been these units that have relied solely on disposable batteries – using solar technology was simply not technologically

110 Burger, K., Cook, N., Koch, A., Sirak, M. (30 April 2003) What Went Right? *Jane's Defence Weekly*, pg. 11

feasible. With the adoption of the PVPCT, this capability gap can be filled by allowing these remote-operating units to become more self-sufficient. This technology allows, for the first time, the use of rechargeable batteries to become an option for military forces working away from their logistics infrastructure for a prolonged period. It is with these groups specifically that the PVPCT appears to have the greatest utility.

F. THE RIFLEMAN'S LOAD AND COMBAT CAPABILITY

Earlier, various types of combat loads were defined. Although these combat load categories are doctrinal, the realities of specific operations often necessitate some deviation from doctrine. For example, the various loads described above were meant for use in conventional combat operations wherein motor transportation assets are available. Under ideal circumstances, when conducting a tactical movement, troops carry something resembling an approach march load. When contact is made with the enemy or upon reaching a designated rally point, all unnecessary equipment is dropped and the troops carry only their fighting loads into the assault. Discarded equipment is then carried to the objective by follow-on units or logistics trains during consolidation.

Operations such as those currently conducted by American troops in Iraq and Afghanistan necessitate a variation from this doctrine, though for different reasons. In the case of Iraq, almost every major operation undertaken since the initial invasion has been conducted on urban terrain. In operations such as the recent operation in Fallujah, troops were in almost constant contact with the enemy. Until the latter portion of the operation, there was no true "consolidation phase" in the traditional sense, wherein a newly captured position is organized and strengthened for use against the enemy. Consequently, soldiers and Marines had to carry something resembling an approach march load for the duration of the operation. During the eight day offensive, embedded journalists reported that Marine infantryman, who moved through Fallujah almost exclusively on foot, carried 75 pound packs throughout the duration of the operation.[111]

In operations in Afghanistan, much of the terrain is impassible to vehicles that normally assist in carrying portions of the combat load, or bringing discarded equipment

111 Filkins, D. (21 November 2004) In Fallujah, Young Marines Saw the Savagery of an Urban War. *The New York Times*.

to an objective following an assault. Like their brethren in Iraq, these infantrymen are forced to carry their approach march loads throughout the duration of most of their operations. These two real life scenarios point to two conclusions: (1) there needs to be a change in doctrinal load carriage. Fm 21-18 was last revised in 1990, when many tactics, techniques, and procedures were still geared toward a bi-polar confrontation with Soviet-style conventional forces. (2) Equipment needs to be developed that allows the infantryman to carry an approach march-type load without the weight penalty that is incurred with the current equipment included in an approach march load.

There has recently been a push within the DoD toward lighter mobility for ground combat forces. The introduction of the M-Gator and the Multi-Purpose Cart by the Army and the Marine Corps are examples of this.

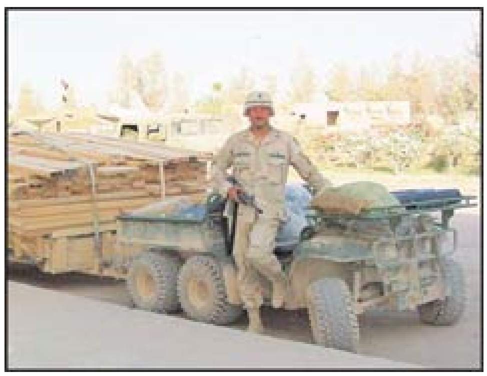

Figure 25. M-Gator in Afghanistan

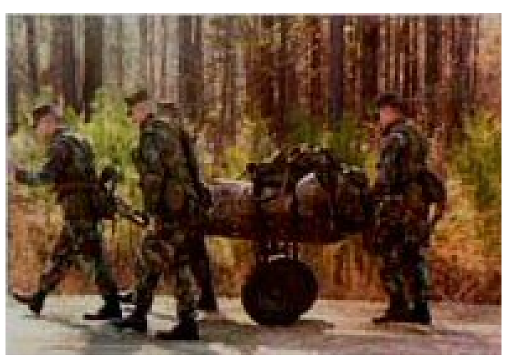

Figure 26. The Multi-Purpose Cart

Yet, it seems that most of these innovations were only meant as lighter-weight methods of helping combat troops carry more gear into the fight. There are few innovations that enable soldiers to operate at least as efficiently as they currently can in combat, while simultaneously lessening physical strain either getting to the fight or while engaged in combat.

In 1950, the noted military theorist Colonel S.L.A. Marshall published *The Soldier's Load and the Mobility of a Nation*. The thesis behind this work was simple: "No logistical system is sound unless its first principle is the enlightened conservation of power of the individual fighter."[112] Marshall advocates that the most precious assets in any army are the physical strength and mental agility of its troops on the firing line.[113] He also cites evidence that as a soldier's physical abilities are degraded, so are his abilities to function mentally. Colonel Marshall completes his syllogism by stating that "every extra pound [the infantryman] carries on his back reduces all of his tactical capabilities."[114]

Marshall concludes his treatise with a call for more careful and disciplined logistics planning and execution. In particular, he faults staff planners with loading soldiers according to their own, presumably unenlightened, view of combat. In Colonel Marshall's view, "The staff tended always to load the combat soldier according to his own view of every possible emergency that might confront him. With every member of a staff trying hard to think of every possible contingency, and no one above the staff enforcing a rigid weight limit to protect the soldier's back, the loads frequently became unsupportable."[115] The role of the staff, and in particular the logistics staff, he argues, should not simply be to support the combat troops, but to relieve them of all unnecessary

112 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pg. iii

113 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pg. 52

114 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pg. 41

115 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pp. 30-31

strain and tension, thereby preserving their primary combat faculties. Unfortunately, it was his observation that history has proven that nothing beyond lip service has been paid to this principle.[116]

In 2003, the army conducted a study entitled The Modern Warrior's Combat Load that verified Colonel Marshall's conclusions. In this study, a combined arms assessment team comprised of experienced infantrymen accompanied the units of the 82nd Airborne Division through several operations in Afghanistan. Their aim was to study the combat load as experienced by a U.S. Army light infantry brigade fighting in desert and mountainous terrain. Data was collected over a two month period in the Afghan spring of 2003 as the division conducted several combat operations against Taliban and Al Qaeda elements.[117] Over the course of their study, the team found that the average light infantryman carries 95 pounds of critical combat equipment in his approach march load when conducting missions of short duration in mild to hot weather.[118] Among the study team's recommendations is that the army assign a Weight Czar with the authority and responsibility to limit the weight and bulk of all developing soldier-borne equipment items and that all pertinent acquisition programs should participate in an overarching weight-reduction program.[119]

Dennis Birch compares the U.S. soldier to a Christmas tree: "Whenever improvements in technology help lighten a soldier's load, someone else wants to hang on a new piece of gear like an ornament." The result is "100 pounds of great ideas hanging off him in all different directions."[120] Mr. Birch works on the Army's Objective Force Warrior program, which attempts to reverse the historical tendency to overload combat troops, while also increasing their capabilities. Objective Force is envisioned to be a

---

116 Marshall, S.L.A (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association, pg. 36

117 U.S. Army Center for Army Lessons Learned (2003). *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan April-May 2003*, Ft. Leavenworth, KS: Center for Army Lessons Learned, pg. 1

118 U.S. Army Center for Army Lessons Learned (2003). *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan April-May 2003*, Ft. Leavenworth, KS: Center for Army Lessons Learned, pg. 87

119 U.S. Army Center for Army Lessons Learned (2003). *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan April-May 2003*, Ft. Leavenworth, KS: Center for Army Lessons Learned, pg. 87

120 Regan, M., The Soldier of the Future Will be Networked, *Laredo Morning Times*, 01 June 2003, pg. 19A. Mr. Regan is an Associated Press writer whose story appeared in the Laredo Morning Times

“system of systems” that includes an array of sensors, communications devices, and robots. This system of systems is centered around the Scorpion combat uniform.

Figure 27. Scorpion Concept Photo

Scorpion is envisioned to include an undershirt integrated with biometric sensors to monitor the soldier’s vital statistics; built-in tourniquets that may be employed remotely; and lightweight body armor that incorporates load carriage for ammunition, water, batteries, and circuits that keep the soldier plugged in to a complex communications network. The crowning jewel of Scorpion, though, is its helmet, which integrates, among other capabilities, un-cooled thermal cameras, a GPS system, a blue-force identification system, and voice communications.

The overall goal of Scorpion, though, is to address Colonel Marshall’s issue of the historic overloading of the combat soldier. The weight goal of the entire Objective Force Warrior system is 40 pounds.[121] In order to meet this weight objective and still be able to provide power to all of the systems envisioned for Objective Force Warrior, a lightweight and, presumably renewable, power source is required. For this, and other future combat systems that are geared toward the goal of reducing the load of the infantryman, PVPCT seems an ideal solution.

G. CONCLUSION

This section demonstrated there are undeniable advantages of using some sort of rechargeable battery system over the use of disposable batteries. At the strategic level of

121 http://www.natick.army.mil/about/pao/pubs/warrior/02/septoct/untangle.htm, 5 November 04

the DoD and the military service, the fiscal advantages are considerable. As shown in Figure 19, the fiscal break-even point for employing rechargeable batteries may be as short as 170 operating hours.

At the operational and tactical levels, though, the combat commander is less concerned with the fiscal cost of an operation than he is with the logistical details involved. In this respect, the use of disposable batteries may seem more attractive than using currently available battery charging technology. In planning for any mission, the commander must not only take into account the scheme of maneuver and fire support plan, but also the sleep plan, the communications plan, the chow and water plan, the casualty evacuation plan, and the plan for dealing with enemy prisoners of war. Given the choice between using disposable batteries versus devising and supervising a rechargeable battery rotation plan, he will almost certainly use disposable batteries. The Program Executive Officer for Soldier System's OIF after-action report states that the soldiers "did not feel rechargeable batteries were sustainable in the field..."[122]

Of course, there are downsides to the tactical decision to use disposable batteries. Short missions, or those of extended duration conducted in close proximity to a robust logistics infrastructure, lend themselves to the use of disposable batteries. However, when conducting an operation of extended duration, the weight of disposable batteries required to conduct such a mission becomes prohibitive. This burden is intensified when considering small units that routinely conduct missions of extended duration with highly constrained re-supply capabilities, such as Special Forces and reconnaissance teams. It seems, thus, that the availability of logistical support should be the overriding tactical consideration when contemplating the use of PVPCT.

There seems to be an inverse relationship between the amount of uncertainty involved in an operation and how dependent a frontline combat unit should be on non-organic logistical support. For example, during a major exercise, the commander can be reasonably certain about many things. The exercise and its subordinate evolutions are scheduled for a known duration, and logistical support is normally analyzed and executed in great detail. Additionally, the consequences of logistical failures during such exercises

122 Smith, LTC J., Operation Iraqi Freedom PEO Soldier Lessons Learned, 15 May 2003, pg. 10

are normally limited to a slip in the exercise schedule and perhaps the sullied reputation of the commander. In contrast, during high intensity combat, very few things are certain and the consequences of logistical failures can be dire. While such operations are planned in perhaps greater detail than any other human endeavor, most leaders are familiar with the axiom that a plan is only good up until the point that one's unit crosses the line of departure.

Curiously, though major exercises and high intensity combat operations seem to lie at the extreme ends of the spectrum of uncertainty, they have something in common: those involved can be reasonably sure of the level of uncertainty associated with each situation. In contrast, the array of missions involved in stability and support operations seems to lie on a transitive point on the spectrum of uncertainty, as shown in Figure 28. That is to say, whereas in high intensity combat operations, those involved in the planning and execution of such operations generally deal with known-unknowns; in stability and support operations, those involved generally deal with more complex unknown-unknowns.

Figure 28. The Spectrum of Uncertainty

The uncertain nature of stability and support operations, especially those conducted in an urban environment, makes the commander's decision on whether or not to employ PVPCT rather difficult. Given the choice between two options of gear and supply loads, the commander will typically favor the option that imposes the lesser weight load upon his troops. As S.L.A. Marshall once observed, "Overloading has never steadied any man or made him more courageous." As stated above, using any rechargeable system becomes more economical in terms of weight than using disposable batteries at the 144th hour of operations for a single battery system.

When one considers the variety of equipment items that may be involved in any operation and the various usage rates of those items, the decision process becomes much more complex. The computer tool developed in conjunction with the Marine Corps Overarching Battery Study was meant to help the commander deal with this complexity. After the variables of mission duration, operating climate, required equipment items, and quantities are input, the user receives a report showing how many disposable batteries are required. The report also shows how many rechargeable batteries are required for the same mission in lieu of disposable batteries. With these figures, along with the corresponding savings information compiled in this study, the financial and weight savings for a typical infantry battalion are readily apparent. The next chapter incorporates these considerations into the final recommendations.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

Chapter V provides conclusions drawn from the analysis in Chapter IV by comparing current disposable battery practices and their associated costs to both current rechargeable technology and Photovoltaic Power Conversion Technology and provides recommendations based upon this breakdown.

B. CONCLUSIONS AND RECOMMENDATIONS

1. PVPCT and the Current Family of Charger Systems Have Value for the Using Units Based Upon the Level of Infrastructure and Mission Profile That They are Currently Operating Within.

a. Conclusions:

1. An appropriate mix of these technologies should be acquired by units and this mix must be based upon their individual, or like units, requirements that take into consideration their access to infrastructure, the anticipated operating environment, and the expected duration of operations.

2. The analysis displays that PVPCT results in greater dollar savings in terms of fuel and electricity costs to the using units through the incorporation of solar power collection. However, the flexibility that is gained by the ability to recharge batteries with a robust infrastructure is a necessary capability, both for efficiency and to compensate for charging batteries in the absence of solar power.

b. Recommendations

1. Combatant Commanders or Major Subordinate Elements Commanders should initiate a fast track acquisition effort to field PVPCT systems to army light infantry and Special Forces as well as Marine Corps infantry and reconnaissance units. Additionally, the U.S. Army Infantry Center and the Marine Corps Combat Development

Command should develop procedures for small units to employ PVPCT and incorporate PVPCT systems into their gear loads.

2. Atira has already configured the system to act as middleman – the system contains one solar array and one PVPCT controller, with a direct plug to a BB-2590, which eliminates the need for a conventional charger. There are no internal batteries in this configuration.

It is recommended that the fielded version of the PVPCT system should have charging slots incorporated for other types of high-rate consumable batteries – namely the rechargeable version of the BA-3058, known commercially as the AA battery. Additionally, the box should contain the capability to interface with a vehicle cigarette lighter and the NATO-standard slave receptacle standard on the HMWWV, the army's Family of Medium Tactical Vehicles, and the Marine Corps' 7.5 ton Medium Tactical Vehicle Replacement to draw a charge off of a vehicle in place of solar power when available.

Figure 29. NATO-Standard Slave Receptacle

Additionally, as other alternative sources become more available (i.e. wind power), a standardized plug to interface with these sources would be ideal, and may also provide more robust around the clock charging capability regardless of weather conditions.

2. Based Upon Usage Level and a Poisson Distributed (and Normal Distribution When Appropriate) Spare Level, Breakeven for the PVPCT Versus Disposable Batteries Will Be Reached at Differing Levels in Terms of Cost and Weight.

a. Conclusion

Duration of missions and the types of equipment that require batteries drive the overall daily battery consumption rates. These factors coupled with accessibility to re-supply drive the load requirements that are to be carried by individual Marines. Not surprisingly, the various users measure the payoff for utilization of rechargeable batteries in different terms. To the basic infantryman, who is solely affected by the amount of weight that he must carry to survive, it is the reduction of heavy batteries to be carried that result in this payoff; however, further up the chain, the costs and logistic supportability involved carry a significantly greater impact. In these two terms, the relevant gains from disposable batteries and PVPCT are reached at two different levels in terms of hours. In analysis of weight, the trade off between disposable batteries and the four BB-2590s with the PVPCT system for a two battery equipment item is reached when the mission requires the using unit to be away from re-supply for as few as 24 hours. In terms of cost, the PVPCT system with four BB-2590s reaches breakeven with disposable batteries at the 220 hour mark at a system cost of $2,184. (Again, this is only for the initial conversion cost.)

One point that bears additional reinforcement is that in terms of cost, as the scope of operations increase, weight becomes a cost driver for logistic support. This increase in operations causes the associated demands placed on the logistic infrastructure to increase as well. With a cost of $19,320 per pallet of disposable BA-5590 batteries on an AMC flight, the idea of weight savings transcends the convenience gained at the lowest level – it becomes a legitimate strategic concern as well.

b. Recommendation

DoD or component fiscal branches should initiate further analysis to study in greater detail the fiscal impact of the adoption of PVPCT. It is also recommended that

they conduct further studies to determine the savings that may be realized by wider fielding of PVPCT beyond light infantry, reconnaissance, and Special Forces units.

C. FINAL NOTE

From the outset of this study it has been clear that the military is facing a shift in not only operating procedures but even more so in its business practices. The move from disposable BA-5590s to rechargeable batteries simply makes sense on all levels. Battery expenditures during Operation Iraqi Freedom, the resulting critical shortages, and the subsequent logistical challenges that accompanied this issue nearly brought coalition offensive operations to a halt. By separating the need to re-supply our battery requirements from the real need – portable power – we begin to shift the focus of what is actually required to fill needs and eliminate capability gaps in the military. If batteries are a reliable addition to the soldier's equipment, he can reduce uncertainty and focus on his mission of engaging and defeating the enemy. With the PVPCT, the ability to recharge batteries becomes a viable option, not just for units in garrison, but particularly for the soldiers who are deployed to the forward edge of the battle area.

From a logistical perspective, this shift towards self-sustainment means that high demand lift capabilities are freed up to focus on movement of other critical materials such as ammunition or medical supplies. The rechargeable batteries impart enormous benefits well beyond the tactical level of logistical support, and in reality, they have the greatest cost benefit ratio when analyzed from the perspective of a theater wide logistics structure. The knowledge that thousands of disposable batteries, worth millions of dollars, are currently infused throughout the supply chain is staggering. From stateside production to worldwide distribution, the idea of filling a current requirement with a small fraction of current expenditures is remarkable and is indicative of the type of Return on Investment that may be realized by DoD wide adoption of rechargeable batteries and the PVPC technology.

Current chargers used by the DoD provide an effective and efficient means to recharge batteries; however, they are too cumbersome and require access to a vehicle, generator, or AC power source to provide power for the recharge. Use of these chargers should be maximized with vehicle mounted troops or those units having adequate power

infrastructure to run the battery chargers because these chargers are currently faster and more robust than the PVPCT in charging a large volume of batteries. It is with the individual Soldier and Marine that the maximum gains are to be realized with the PVPCT. By utilizing this technology and a flexible solar panel, he gains the ability to be self supporting in terms of his power requirement. Of additional value, the PVPCT may play an active role in providing emergency power to downed pilots or stranded Marines when they experience vehicle break downs in remote regions. In its current configuration, the PVPCT gives our Marines an added capability that can directly impact the execution of missions or in providing a safety net for power requirements.

It is clear that military equipment in the future will require ever increasing amounts of power. Either the logistics system supplies it or soldiers do. It is foolish and nearing impossibility to constantly supply battery power to units. The lessons of Iraq and Afghanistan clearly show that soldiers and marines must be able to generate their own ever increasing power needs.

In closing, we fully believe that Atira's technological innovation is a tool that has a significant ability to impact the daily operations and costs of the United States military. In our analysis it has become obvious that the impacts on the logistical chain are substantial enough to push for incorporation of this technology at the earliest possible date. We also believe that we have only lightly scratched the surface of the utility that may be gained by future applications of this product. We encountered several areas that fell beyond the scope of our study but we feel are worthy of continued analysis.

D. AREAS OF FUTURE ANALYSIS

1. Reduced Fuel Consumption Rates

Through the course of our research, it became apparent that fuel consumption rates and the logistics involved with providing generator support can be significant cost drivers in terms of logistic support. It is worthwhile to evaluate the impact on fuel consumption with respect to logistics and environmental aspects that may be realized by maximum incorporation of PVPCT to recharge batteries in garrison via more efficient,

semi-permanent solar collectors. In this regard, an analysis of the per hour cost between solar energy and fossil fuels should be performed. In other words, which is cheaper? The cost of PV power with the PVPCT may have fallen below the cost of oil, especially with the recent cost surges of oil. This analysis could take into account the geopolitical aspects of the global oil market. If the U.S. reduced its oil consumption by a mere 10%, what effect will that have on the Middle East? Would that undermine the Middle East's political influence in U.S. politics?

2. PVPCT Incorporation into Individual Equipment

The next step appears to be incorporating the power generating technology into an individual soldier's or Marine's equipment to provide constant power output. Such methods could involve solar collection, wind driven devices, or even kinetic sources that would provide power through Atira's power conversion technology. A study should be conducted that evaluates the feasibility and application of the PVPC technology into the individual soldier's personal equipment.

3. PVPCT Providing Limited Power to Shelters

During field evolutions, a number of equipment items, such as portable shelters or fire control radars, require generator support for the minimal power requirement they impose. In fact, many of these structures have designated generator support merely to run interior lights or a small number of computers. The generators for these locations involve a tremendous logistic burden, to include HAZMAT compliant fuel pits, maintenance, and additional fuel delivery routes. Many of these sites with low power requirements may benefit from utilizing alternative power sources, specifically PVPCT packages to replace current generator requirements.

4. Lease Versus Buy

In the acquisition process, one valid avenue to assess is the possible benefit of leasing these assets as compared to purchasing them outright. This shifts the risk from military users to suppliers but might have unforeseen costs because of the potential loss

or damage to these systems that would doubtfully be absorbed by suppliers. However, there may be utility in examining the possibility of contracting with Atira to lease a certain level of capability, i.e., a certain number of complete systems to include a sufficient number of BB-2590 batteries, controllers and solar arrays of various sizes and capabilities.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Bowden, Mark, *Blackhawk Down; A Story of Modern War*, New American Library, NY, 1999, p. 44

Burger, K., Cook, N., Koch, A., Sirak, M. (2003, April 30) What Went Right? *Jane's Defence Weekly*, p. 11

Defense Standardization Program Case Study 2002: Army Battery Standardization – Rechargeable Batteries Power the Future Force, pp. 3, 5

Dept. of Energy, Solar Energy Profile, http://www.eia.doe.gov/cneaf/solar.renewables/page/solarthermal/solarprofile.pdf, 30 September 2004

Fein, Geoff S., Battery Supplies Ran Dangerously Low in Iraq, *National Defense*, Arlington Press, Sep 2003, Vol. 88, Iss. 598, p. 16

Filkins, D. (21 November 2004) In Fallujah, Young Marines Saw the Savagery of an Urban War. *The New York Times*.

Hanlon, LtGen E.J., MCO 3500.11E: Marine Corps Combined Arms Exercise (CAX) Program, signed 21 November 2001, p. 3

Headquarters, Department of the Army (1990). *FM 21-18: Foot Marches*, Washington, DC: U.S. Government Printing Office, p. 5-6

Headquarters, Marine Corps Programs and Resources Department (2000).*United States Marine Corps Concepts & Issues 2000: Leading the Pack in a New Era*, Washington, D.C.: U.S. Government Printing Office, p. 96

http://ces.iisc.ernet.in/hpg/envis/olydoc712.html, 30 September 2004

http://encyclobeamia.solarbotics.net/articles/photovoltaic.html, 30 September 2004

http://inventors.about.com/library/inventors/blsolar2.htm, 29 September 2004

http://www.batteriesdigest.com/iraqi.htm, 26 September 2004

http://www.bren-tronics.com/pdf/BB2590.pdf, 17 September 2004

http://www.bren-tronics.com/pdf/BB390B.pdf, 17 September 2004

http://www.californiasolarcenter.org/photovoltaics.html, 30 September 2004

http://www.darpa.mil/dso/thrust/matdev/palmpower/presentations/hartman.pdf, 28 September 2004

http://www.defense-update.com/products/b/bb2590.htm, 24 September 2004

http://www.defense-update.com/products/b/ba5590.htm, 24 September 2004

http://www.defenselink.mil/speeches/1997/t19970311-lynn.html, 24 September 2004

http://www.designation-systems.net/dusrm/m-71.html, 07 October 2004

http://www.dsd.es.northropgrumman.com/laser/GLTD.html, 07 October 2004

http://www.dsp.dla.mil/documents/cases/Army-battery-stdzn.pdf, 26 September 2004

http://www.fas.org/man/dod-101/sys/land/javelin.htm, 07 October 2004

http://www.fas.org/man/dod-101/sys/land/m22-acada.htm, 07 October 2004

http://www.globalsecurity.org/military/systems/ground/an-peq1.htm, 07 October 2004

http://www.hqmc.usmc.mil/factfile.nsf/0/4ba8f1e3958ca16d8525628100789abb?OpenDocument, 07 October 2004

http://www.iowathinfilm.com/products/rollableseries/index.html, 05 October 2004

http://www.marcorsyscom.usmc.mil/sites/pmcom/sincgars.asp, 05 October 2004

http://www.mcs.drexel.edu/~crorres/Archimedes/Mirrors/Tzetzes.html, 30 September 2004

http://www.natick.army.mil/about/pao/pubs/warrior/02/septoct/untangle.htm, 05 November 2004

http://www.nyu.edu/globalbeat/syndicate/burgess102803.html, 28 September 2004

http://www.public.amc.af.mil/business/fm/fy04dod.pdf, 28 September 2004

http://www.rfcomm.harris.com/products/tactical-radio-communications/an-prc-150-hq.pdf, 07 October 2004

http://www.romad.com/equipment.htm#PRC-117F, 05 October 2004

http://www.tpub.com/content/USMC/mcr3403b/css/mcr3403b_32.htm, 05 October 2004

http://www.uccs.edu/~energy/courses/160lectures/solhist.htm, 28 September 2004

http://www.ultralifebatteries.com/techsheets/UBI-5107_UBI-2590.pdf, 26 September 2004

http://www.uni-solar.com/cons_products.html, 05 October 2004

http://www.walter-fendt.de/ph11e/photoeffect.htm, 29 September 2004

https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary85256A2B0062C0F7.nsf, 28 September 2004

https://lrc7.monmouth.army.mil/QuickPlace/ipm/PageLibrary.nsf, 28 September 2004

Marshall, S.L.A. (1980), *The Soldier's Load and the Mobility of a Nation*. Quantico, VA: The Marine Corps Association. (Original work published in 1949), pp. iii, 3, 30-31, 36, 41, 52

Marine Corps Systems Command. (2004). *U.S. Marine Corps Overarching Battery Study* (MCSC Contract Number M00264-01-D-0002). Quantico, VA: Marine Corps Systems Command, pp. ES-1, I-3, I-5, II-18, B-6 – B-31, C-7 – C-49

Marine Corps Systems Command Liaison Team, Field Report, 20-25 April 2003, p. 7

Norman, http://www.eco.utexas.edu/homepages/faculty/Norman/long.extra/Student.F99/solar/car.html, 28 September 2004

Navy Cooperative Research Agreement, NPS and ATIRA, Low-Light Solar Charger, p. 7

Naval Postgraduate School Graduate School of Business and Public Policy Programs, http://www.nps.navy.mil/gsbpp/programs.htm, 18 October 2004

Perlin and Butti, http://www.californiasolarcenter.org/history_solarthermal.html, 29 September 2004

Perlin and Butti, www.californiasolarcenter.org/history_passive.html, 29 September 2004

Perlin and Butti, http://www.californiasolarcenter.org/history_pv.html, 28 September 2004

Regan, M., Soldier of the Future Will be Networked, *Laredo Morning Times*, 01 June 2003, p. 19A

Smith, http://www.solarenergy.com/info_history.html, 30 September 2004

Smith, LTC J., Operation Iraqi Freedom PEO Soldier Lessons Learned, 15 May 2003, p. 10

Third Infantry Division (Mechanized) After Action Report: Operation Iraqi Freedom, p. 196

U.S. Army Center for Army Lessons Learned (2003). *The Modern Warrior's Combat Load: Dismounted Operations in Afghanistan April-May 2003*, Ft. Leavenworth, KS: Center for Army Lessons Learned, pp. 1, 87

www.californiasolarcenter.org/history_passive.html, 29 September 2004

www.centcom.mil/CENTCOMNews/Stories/09_04/28.htm, 28 September 2004

www.encarta.msn.com/encylopedia_761562112/Sun.html, 28 September 2004

www.solarserver.de/lexikon/sonnenenergie-e.html, 28 September 2004

www.usgs.gov/tech-transfer/what-crada.html, 29 September 2004

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Marine Corps Representative
   Naval Postgraduate School
   Monterey, CA

4. Director, Training and Education, MCCDC, Code C46
   Quantico, VA

5. Director, Marine Corps Research Center, MCCDC, Code C40RC
   Quantico, VA

6. Marine Corps Tactical Systems Support Activity (Attn: Operations Officer)
   Camp Pendleton, CA

7. Lieutenant General J.R. Vines
   XVIII Airborne Corps
   Ft Bragg, NC

8. Dr. Lynn Samuelson
   Defense Advanced Research Projects Agency
   Natick, MA

9. Mr. Michael Gallagher
   Marine Corps Systems Command
   Quantico, VA